JET PROPULSION IN COMMERCIAL AIR TRANSPORTATION

The Edwin G. Baetjer II Memorial Lectures

JET PROPULSION IN COMMERCIAL AIR TRANSPORTATION

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1948
PRINCETON UNIVERSITY PRESS
PRINCETON, NEW JERSEY

LONDON: GEOFFREY CUMBERLEGE, OXFORD UNIVERSITY PRESS

PRINTED IN THE UNITED STATES OF AMERICA
BY NEW YORK LITHOGRAPHING CO. AT NEW YORK, N.Y.

PREFACE

In 1945 the late Edwin G. Baetjer of Baltimore bequeathed to Princeton University a generous endowment in memory of Lieutenant Edwin G. Baetjer II, his nephew and namesake. Lieutenant Baetjer had been one of the first Princeton students to graduate from the University's new Department of Aeronautical Engineering and enter the U. S. Army Air Forces. He met death in July 1944 near Chengtu, China, while serving as Flight Engineer in one of the earliest B-29 bomber squadrons to reach the Asiatic Theater.

The Edwin G. Baetjer Memorial Fund has since its establishment been used to enrich Princeton's formal instruction in aeronautical engineering through an expanding program of lectures, seminars, colloquia and conferences on aeronautical topics which have already brought to the University some of the outstanding leaders in the aviation world.

The material in this book represents the first series of Edwin G. Baetjer II Memorial Lectures to be prepared for publication. It is purposely devoted, therefore, to what we consider one of the outstanding questions which today challenge aeronautical engineers - "Can Jet Propulsion, which has so revolutionized Military Aviation, be applied

to advantage in Civil Air Transportation?" In presenting the splendidly organized, authoritative answer set forth in this book, Robert E. Hage has brought to this task a background of immediate and responsible study of this question which, in our judgment, is but rarely matched throughout the aeronautical engineering profession.

A graduate of the University of Washington, the author completed graduate work at the Massachusetts Institute of Technology, taught briefly at his alma mater, entered the U. S. Army Air Forces, rose to the rank of Major and became from 1944 to 1946, Military Director of the Aerodynamics Branch of the Aircraft Laboratory at Wright Field in Dayton, Ohio. In that post he had, of course, much to do with the first applications of Jet Propulsion to military aircraft design. Since leaving the service he has been a Senior Group Engineer in the Preliminary Design Section of the Boeing Airplane Company, where his assignment has coincided almost exactly with that set forth as the basis for this volume.

We feel that this resulting presentation comes up fully to the high standards which we had hoped to set in this first publication to result from the establishment of the Baetjer Fund.

The author has asked that special acknowledgment be made here to Miss Alice I. Dethman, Mr. Maynard L. Pennell

and Mr. Richard D. Fitzsimmons of the Boeing Airplane Company and to Mrs. Agnes F. May of Princeton for their assistance in the preparation of the manuscript.

Daniel Sayre

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January 1948

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JET PROPULSION IN COMMERCIAL AIR TRANSPORTATION

CHAPTER I

EVOLUTION OF SPEED

The aircraft designer entered the period of World War II with one type of power plant available for installation on military airplanes - the internal combustion engine. He emerged with this engine developed to a stage approaching a practical limitation in size and horsepower output, and four radically new types - the rocket, ramjet, turbojet, and a combination of the turbojet with a conventional propeller called the turbine propeller or turboprop.

All of these new power plants had, by 1947, been applied experimentally to military airplanes and guided missiles. For example, the turbojet engine has been used with considerable success in such Army Air Force fighters as the P-80 and P-84. The same engine has been used in such bombers as the B-45 and B-47. A turbine propeller engine has been used on both Army and Navy experimental fighters. The rocket power plant was used successfully on the German V-2 missile. The rocket is now installed on experimental high-speed airplanes in an attempt to reach supersonic speeds in piloted aircraft. The ramjet power plant is being developed and applied to missiles designed for supersonic flight speeds.

These new power plants are so far characterized by using, in comparison to the reciprocating engine, large quantities of fuel and of obtaining in general the most

efficient operation in fuel economy at speeds and altitudes above those associated with reciprocating engine aircraft. Mounted on transport aircraft, these engines would permit flight at far greater speeds and higher altitudes, but at the same time they would require greater fuel costs than the commercial transport of today.

Looking into the future some twenty to thirty years, a rocket or ramjet propelled transport may enable a passenger to cross the United States from coast to coast in an elapsed time of one to two hours. The ramifications of such a Buck Rogers ship are as yet unexplored and unknown, but the feasibility of a turbojet or turboprop transport to fly the same distance in five hours is quite probable within the next decade.

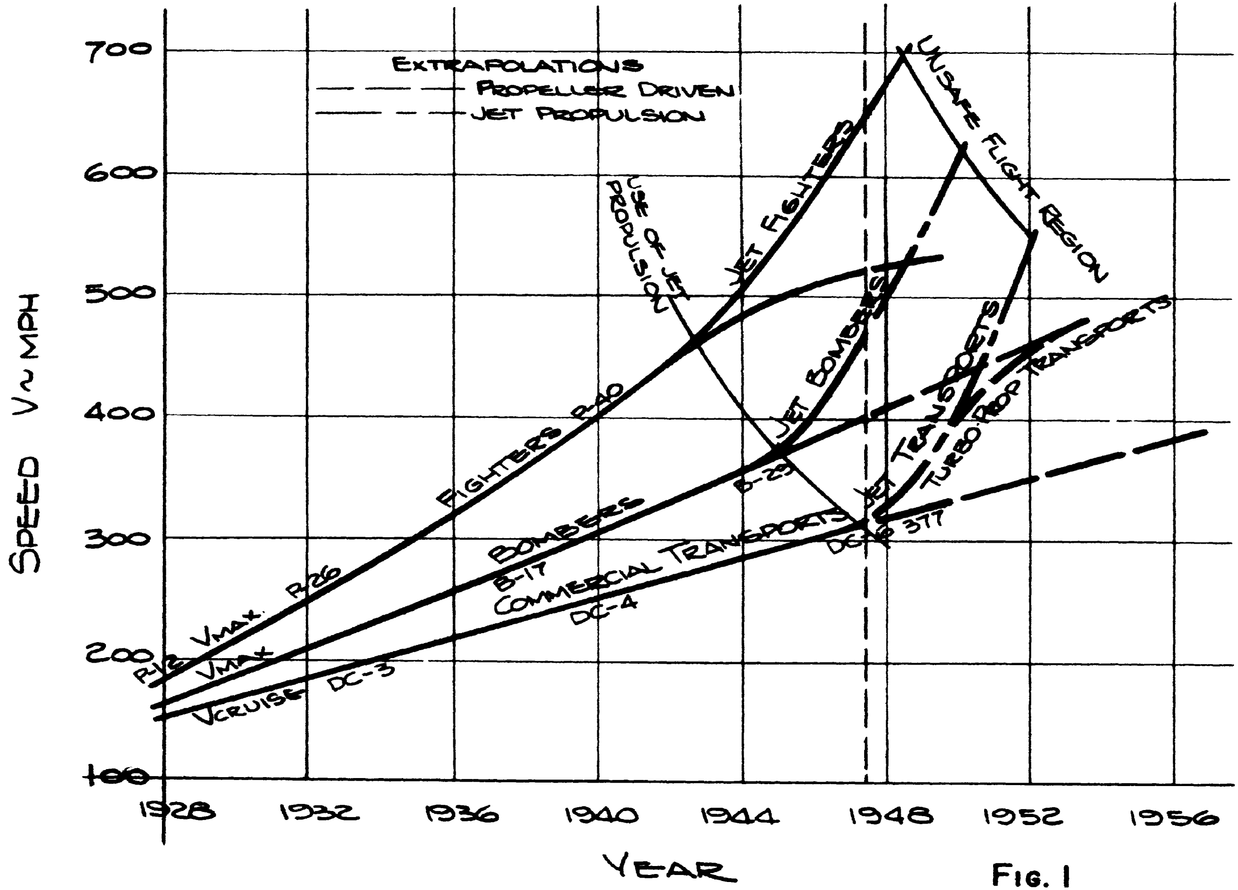
Before predicting the advancement of commercial transportation for the next five or ten years, an examination of Figure 1 may give some clue regarding the extrapolation of speeds for the future. (In the realm of fighters, the American and British jet fighters are approaching speeds of approximately 650 miles per hour. Jet bombers are approaching speeds of 550 to 600 mph, whereas reciprocating-engine bombers are approaching speeds of 400 mph. Thus it may be seen by extrapolating the reciprocating-engine commercial transport ten years away, a speed of 400 mph is very probable. By following similar trends, however, in the advancements in speeds associated with the use of jet propulsion on bombers and fighters, speeds of 525 mph for a turbojet transport and 450 mph for a turboprop

transport appear possible by 1952. At the present stage of the art of aircraft design, flights much above 525, 600 and 700 mph are considered unsafe for commercial airplanes, bombers and fighters respectively.

In the field of commercial transportation, the goal of the airlines in satisfying the public demand has and always will be increased speed, if at the same time this is accompanied by improvements in safety, comfort, reliability, and economy. Whether these power plants can be applied economically depends on whether the added speed will entail greater total operating costs. A discussion of the effect of speed on safety, reliability and comfort will also clarify the picture for the jet transport of tomorrow.

By analyzing the operating costs of different types of transports the direct operating costs can be determined mathematically whereas the comparison of indirect operating cost can at the present only be generalized. The direct operating cost of any type of transport may be expressed quite logically and fundamentally in terms of cents per ton mile. Since most direct operating costs are a function of time, cents per hour divided by miles per hour gives cents per mile, and cents per mile divided by tonnage carried gives cents per ton-mile. The direct operating cost of air transportation in cents/ton-mile is affected by:

1. Cost per hour of fuel, airframe, engine and crew



EXTRAPOLATIONS
PROPELLER DRIVEN
JET PROPULSION
700
600
500
400
300
200
100
SPEED V ~ MPH
1928
1932
1936
1940
1944
1948
1952
1956
YEAR
UNSAFE FLIGHT REGION
JET FIGHTERS
USE OF JET PROPULSION
JET BOMBERS
JET TRANSPORTS
TURBO-PROP TRANSPORTS
FIGHTERS
P-40
P-26
VMAX
BOMBERS
B-17
B-29
COMMERCIAL TRANSPORTS
DC-4
DC-3
VCRUISE
377

FIG. 1

2. Payload

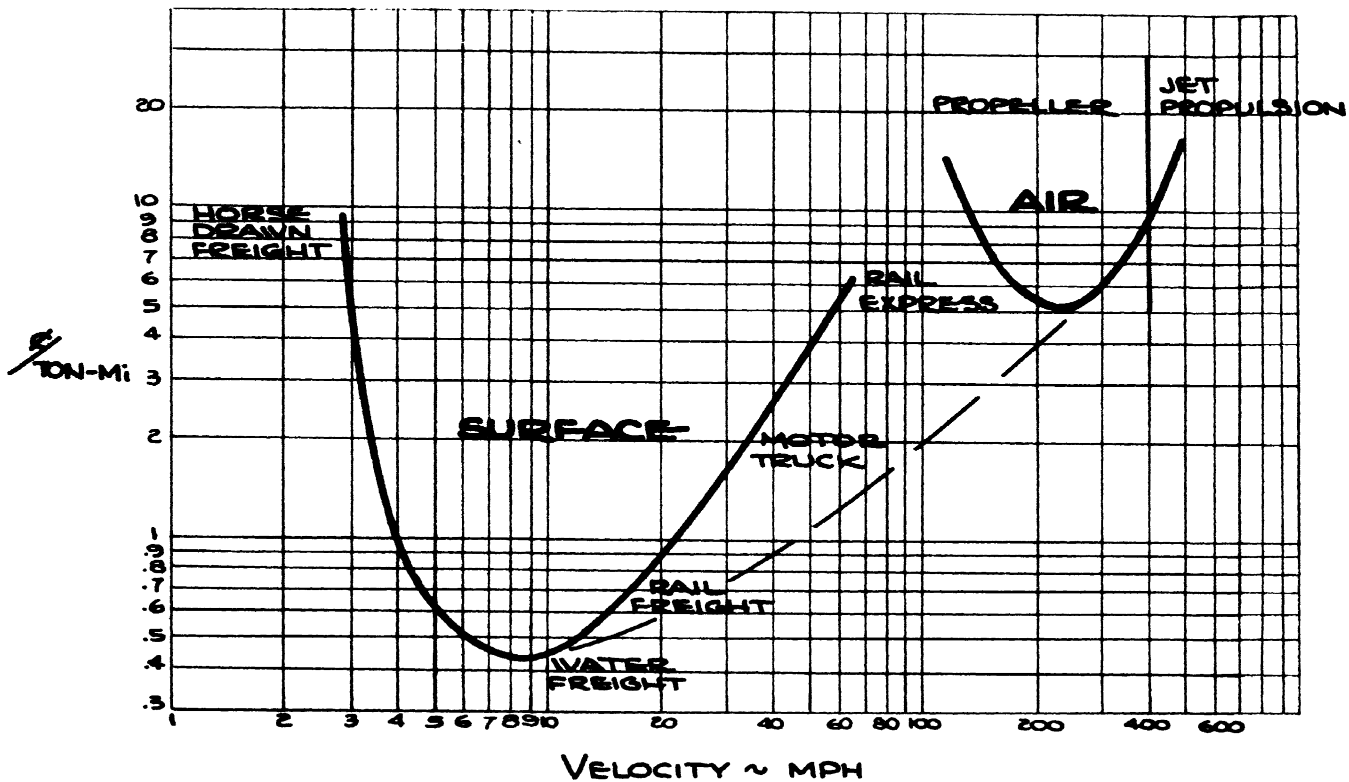
3. Block-to-block speed

Direct operating costs vary inversely as payload and speed, and directly as the cost per hour of operation. Block-to-block speed is defined as the total distance divided by the total flight time, and in the case of air transports is defined by the following equation.

$$V_B = \frac{\text{Distance}}{\text{Time}_{\text{climb}} + \text{Time}_{\text{maneuver}} + \text{Time}_{\text{cruise}}}$$

Figure 2 shows the effect of speed on direct operating costs for both surface and air transportation. It appears from this chart that an optimum speed for lowest cost is reached for both surface and air transportation. Above this optimum, premimums in cost are paid for premimums in speed. However, the indirect expenditures of transportation such as payroll of personnel, administration expenditures, sales and public relation expenses, and building and facility expenses can no longer be calculated as a function of speed of the carrier. It will be shown later that some of these indirect expenses are influenced by speed and may even be lower as the speed of aircraft increases up to a certain limit. In Chapter 4 is presented a detailed analysis of direct operating costs for reciprocating engine, turboprop and turbojet powered commercial aircraft.

The availability of turboprop and turbojet engines regardless of cost comparisons will probably dictate the



DIRECT OPERATING COST vs SPEED

FIG. 2

next future type of jet transport. In the United States as well as England the turbojet engine is approximately two years ahead of the turboprop in its development. In the turbojet field many promising designs both here and abroad are now available and are continually being improved both as to reliability and thrust output. The Rolls Royce Nene, Allison I-40 and General Electric TG-190 engines will offer a range of maximum static thrust output of between 5000 and 8000 lbs during the next five years. The turbine propeller outlook is not as promising, and, with the exception of small 1000-2000 horsepower engines like the Armstrong-Siddeley Mamba and Bristol Theseus, the likelihood of a larger practical engine for commercial application is not promising before 1952.

The following excerpts illustrate the current thinking regarding the next type of jet transport. Following this is the author's own prediction of the future jet transport.

> From "Skyways", March 1947: In the United States American Airlines' C. R. Smith is reported to have said that as soon as the Nene has been tested for a 500-hour span between overhauls (present airline practice on reciprocating engines is 600 to 750 hours), AA will be in the market for a high-speed jet transport. This was after he and Harold Harris, vice-president of American Overseas Airlines, had returned from European conferences with technical authorities on jet propulsion power.

> From "Transport Aircraft Powerplant Outlook for 1947" by R. C. Loomis, Director of Engineering and Overhaul, Trans World Airline: The year 1947 will not see the introduction of any gas turbine powered aircraft to commercial service, at least in the United States. This paper would not be complete, however,

without a few comments on gas turbine propeller and turbojet engine types.

The turbine-propeller engine is being extensively developed here and abroad because this type can most easily be adapted to existing aircraft designs and because, in theory, this type promises the greatest gains in increased performance and payload, particularly on long range flights. After discussing the propeller drive and speed control problems with those engaged in this work, however, the author has concluded that turbine-propeller powerplants are still several years from being practical for airline use.

In contrast, turbojet powerplants are today being extensively used in military aircraft, and they have reached such a state of development that they could be successfully used in commercial operations today if the proper aircraft were available. Since new aircraft models must be developed in order to efficiently use turbojets, however, it appears that the introduction of turbojet-powered commercial transports into scheduled service is at least three years away.

The airline operators are not immediately interested in supersonic speeds because of the attendant operational problems, but the early introduction of a medium range, 450 mph, turbojet-powered transport is both desirable and feasible.

A turbojet powered transport would offer not only a substantial increase in cruising speed, but almost vibrationless and noiseless flight [within the cabin], all extremely desired from a passenger sales standpoint.

In addition, the simplicity of structure and control system associated with turbojet engines offer attractive possibilities for maintenance cost reduction.

In the author's opinion, a medium-range turbojet transport carrying 25 to 30 passengers and flying at a cruising speed of 500 to 525 mph is an extremely likely development for use on the routes of the major airlines between major centers of population by the close of the year 1950. In order to justify the above prediction it is now necessary to examine in some detail the powerplant, aerodynamic, economic and operational problems associated

with relatively high-speed flight.

CHAPTER II

BASIC POWER PLANT CHARACTERISTICS

In recent years the practical methods of propulsion have increased to include in addition to the reciprocating engine as a power plant four other basic types, turboprop, turbojet, ramjet, and rocket, characterized by different features of construction, operation, and performance. In Figures 3, 4 and 5 are presented typical performance data for these different types, including schematic diagrams and performance curves. All of these propulsive devices can be considered as heat engines which convert fuel energy into useful work done on the airplane. The overall efficiency of each power plant can be expressed as the per cent of total heat energy of fuel and oxidizer that is converted into useful work. This efficiency can be further broken down as a multiple of propulsive efficiency and thermal efficiency. Thermal efficiency is the per cent of total heat energy of fuel and oxidizer that is converted into mechanical energy, and propulsive efficiency is the per cent of this mechanical energy which is converted into useful work done on the airplane.

In short, all propulsive devices consist of a heat engine which converts heat energy into mechanical energy in combination with a system that converts the mechanical energy into useful thrust. The parameters presented in Figures 4 and 5 depend on the overall efficiency of each

power plant and permit a basis by which each type can be fairly compared.

The thermal efficiency of each unit represented in Figure 3 is somewhat higher for the rocket than the other types because pressure energy is built into the oxidizer before it is placed in the rocket. In the other engines the oxygen (air) is compressed during the cycle. The ramjet is very inefficient at low speeds because compression is dependent on the natural flow of air through the intake diffuser.

For the following discussion the rocket is eliminated as a practical type of power plant for the jet transport of tomorrow due to the extremely high fuel consumption as compared to the other types of power plants (see Figure 5). For any appreciable ranges, the large size of a rocket transport necessary to enclose both payload and fuel would prohibit any reasonable economy of operation. The ramjet is also eliminated as a possible type of power plant due to its inability to operate at low and medium speeds. Of the three remaining types, a discussion of propulsive efficiency will indicate the possible uses of each type in various speed regions. The propulsive efficiency equation for a turbojet, ramjet or any propulsive system which accelerates a mass of free air is essentially the same. In the case of the turbojet, the fuel weight may be neglected since the air to fuel ratio is approximately 50 to 1.

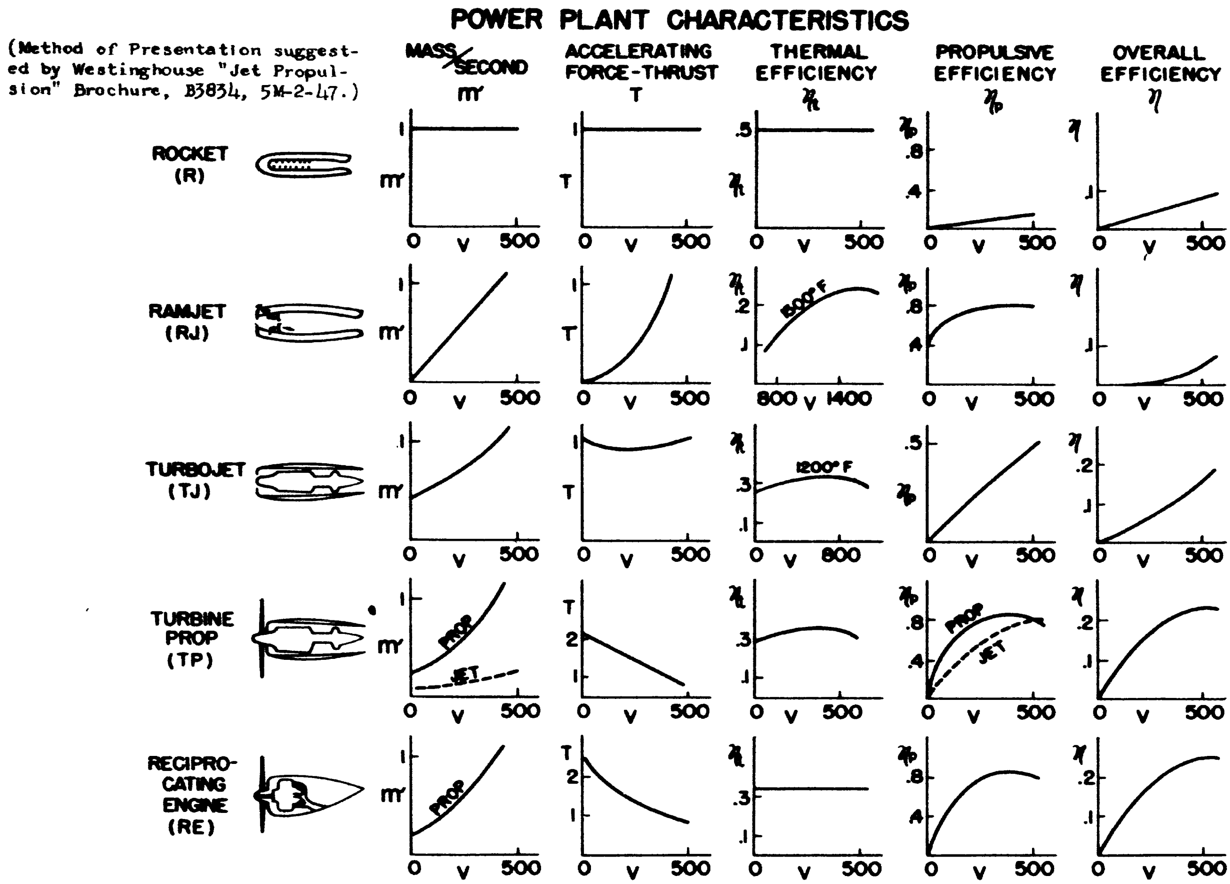
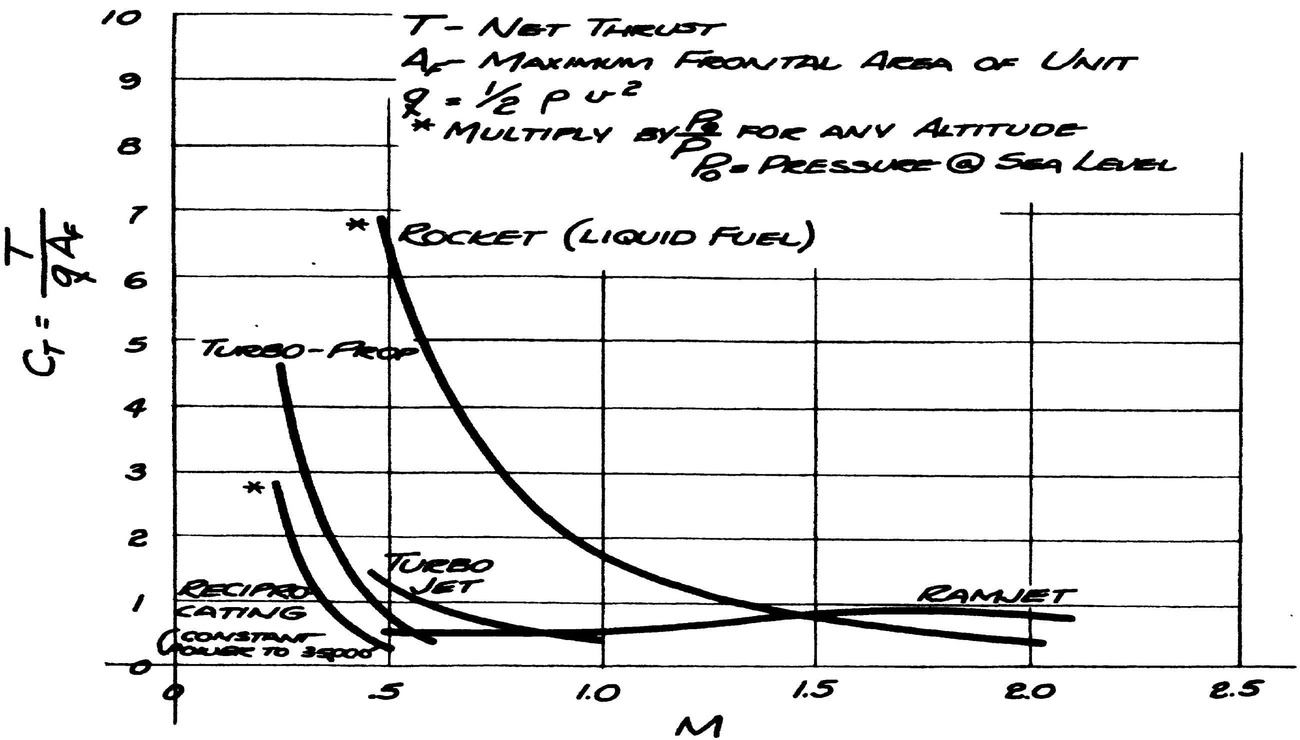

POWER PLANT CHARACTERISTICS
(Method of Presentation suggested by Westinghouse "Jet Propulsion" Brochure, B3834, 5M-2-47.)
MASS/SECOND m'
ACCELERATING FORCE-THRUST T
THERMAL EFFICIENCY η_t
PROPULSIVE EFFICIENCY η_p
OVERALL EFFICIENCY η
ROCKET (R)
RAMJET (RJ)
TURBOJET (TJ)
TURBINE PROP (TP)
RECIPROCATING ENGINE (RE)
800° F
1200° F
PROP
JET
V
0
500
800
1400

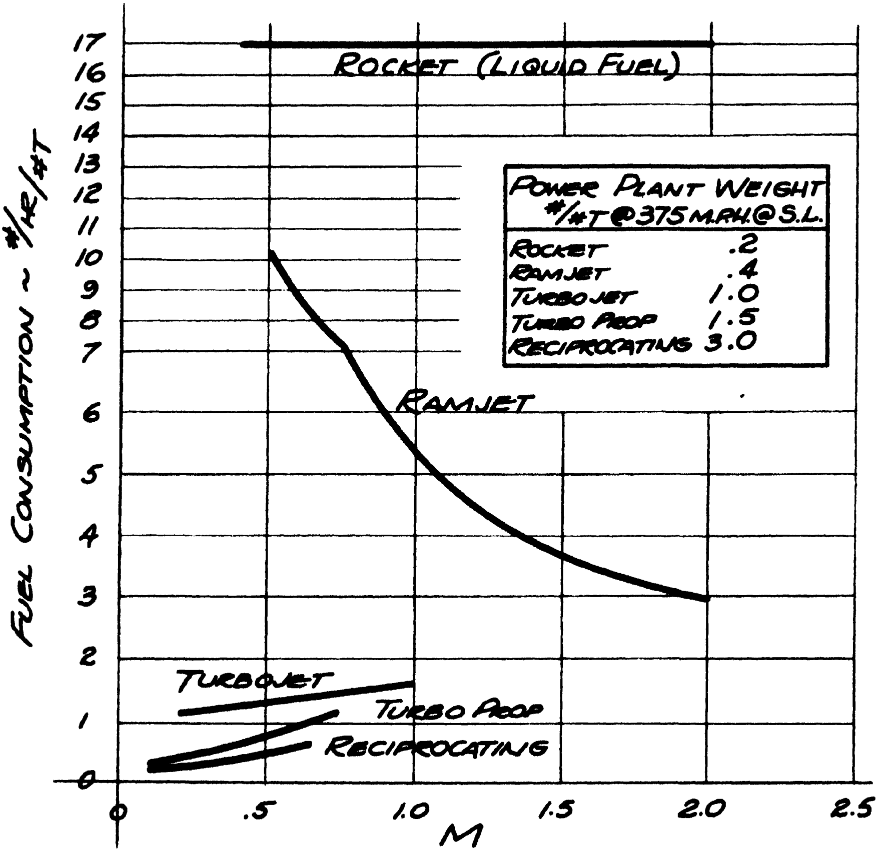
FIG. 3



PROPULSION COMPARISON

SEA LEVEL-35,000'

FIG. 4



FUEL CONSUMPTION COMPARISON

SEA LEVEL - 35,000'

FIG. 5

Defining:

v = Velocity in ft/sec

v_o = Free stream relative velocity in ft/sec

v_w = Wake or slip stream velocity in ft/sec

T = Net thrust in pounds

w = Weight of fuel and oxidizer in lbs/sec

Propulsive Efficiency, $\eta_p = \dfrac{T\, v_o}{1/2\ \frac{w}{g}\ v^2}$

Since thrust is $\frac{w}{g}(v_w - v_o)$ and the mechanical energy produced in the system is the difference between the kinetic energy of the wake and the free stream, then

$$\eta_p = \frac{\frac{w}{g}(v_w - v_o)\ v_o}{\frac{1}{2}\ \frac{w}{g}(v_w^2 - v_o^2)} = \frac{2}{1 + \frac{v_w}{v_o}}$$

This relationship is plotted in Figure 6.

When the slip stream velocity is equal to the free stream velocity the propulsive efficiency is 100 per cent and the thrust zero. When the slip stream velocity exceeds the free stream velocity, the propulsive efficiency decreases. When the slip stream velocity is less than the free stream velocity, then the system is no longer self-sustaining.

For the rocket, useful work divided by mechanical energy produced in the system again defines propulsive efficiency, but in this case thrust is equal to $\frac{w}{g}\ v_w$, since both the fuel and oxidizer experience a change in

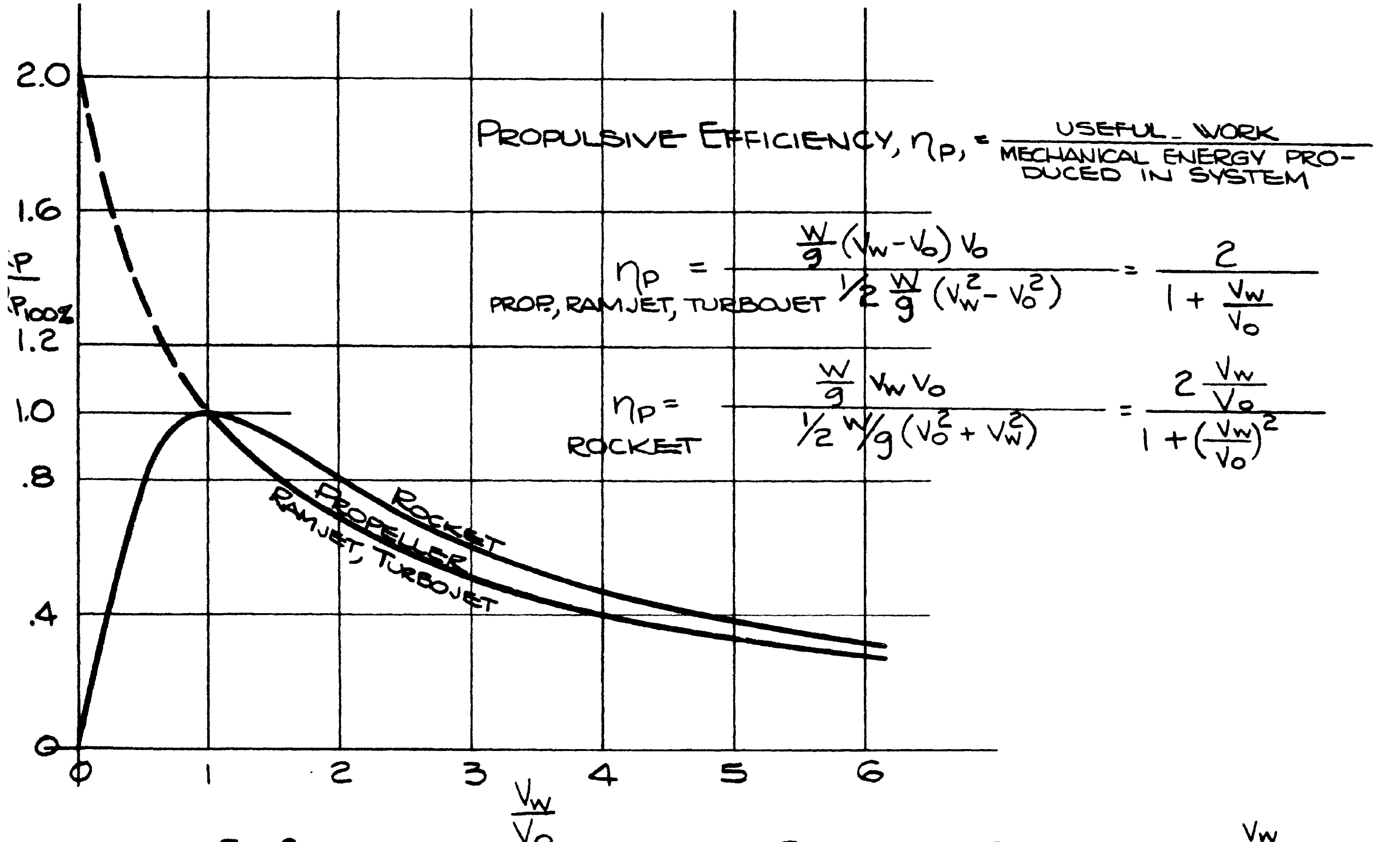


Fig.6

Propulsive Efficiency vs. $\frac{V_W}{V_0}$

speed equal to v_w . The kinetic energy input is equal to $1/2\ \frac{w}{g}(v_o^2 + v_w^2)$ because energy has been supplied to bring the fuel and oxidizer up to the flight speed of the rocket. Therefore, in the case of the rocket,

$$\eta_p = \frac{\frac{w}{g}\ v_w\ v_o}{1/2\ \frac{w}{g}\ (v_o^2 + v_w^2)}$$

$$\eta_p = \frac{2\ \frac{v_w}{v_o}}{1 + (\frac{v_w}{v_o})^2}$$

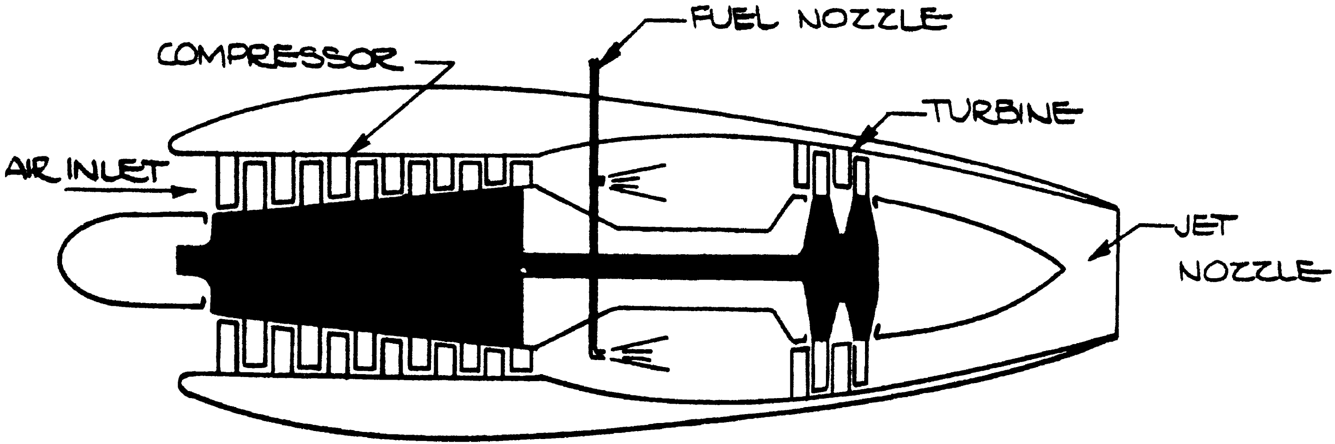
Now even if v_w is less than v_o , the rocket is still self-sustaining and the propulsive efficiency is less than one and falls to zero when v_w is equal to zero. The propulsive efficiency is 100 per cent when v_w is equal to v_o . The propulsive efficiency decreases as v_w becomes greater than v_o . These relationships are plotted in Figure 6.

From Figure 3 it is noticed that the propulsive efficiency for either the turboprop or reciprocating engine approaches a value of .9 at or near high speed (450 mph) of these types of airplanes. This corresponds to a ratio of v_w/v_o of approximately 1.25 (see Figure 6). Since v_w for the turbojet is greater than v_w for the larger diameter and greater mass-flow propeller engines for comparable values of thrust, the energy losses are also greater, producing lower values of propulsive efficiency. The propulsive efficiency of the turbojet is very low at

slow speeds and only about half that of the propeller airplanes at speeds of 400 to 500 miles per hour (v_w/v_o = 3 to 4). In other words, in order to improve the thrust and fuel consumption values of the turbojet, the airplane must fly as fast as possible up to a speed where compressibility difficulties are encountered.

It is noted that at low speeds the thrust characteristics of the propeller engines as indicated in Figure 3 permit superior takeoff and climb performance than can be obtained by the turbojet engine. In Figure 8, by ducting the air through a fan which is integral with a free turbine in the basic unit and permitting the two flows to combine in the nozzle, performance characteristics somewhere between those for a simple turbojet and propeller engine are obtained. In other words, a mass of air of greater diameter is affected, giving a higher propulsive efficiency, higher thrust, and lower specific fuel consumption than for the turbojet. By ducting the air through fans at the inlet as in Figure 8 and permitting part of this air to flow around the compressor and out the jet nozzle, performance characteristics somewhere between those for a straight turbojet and straight propeller engine are obtained. In other words a greater diameter mass of air is affected than in the turbojet, giving higher propulsive efficiency at lower speeds.

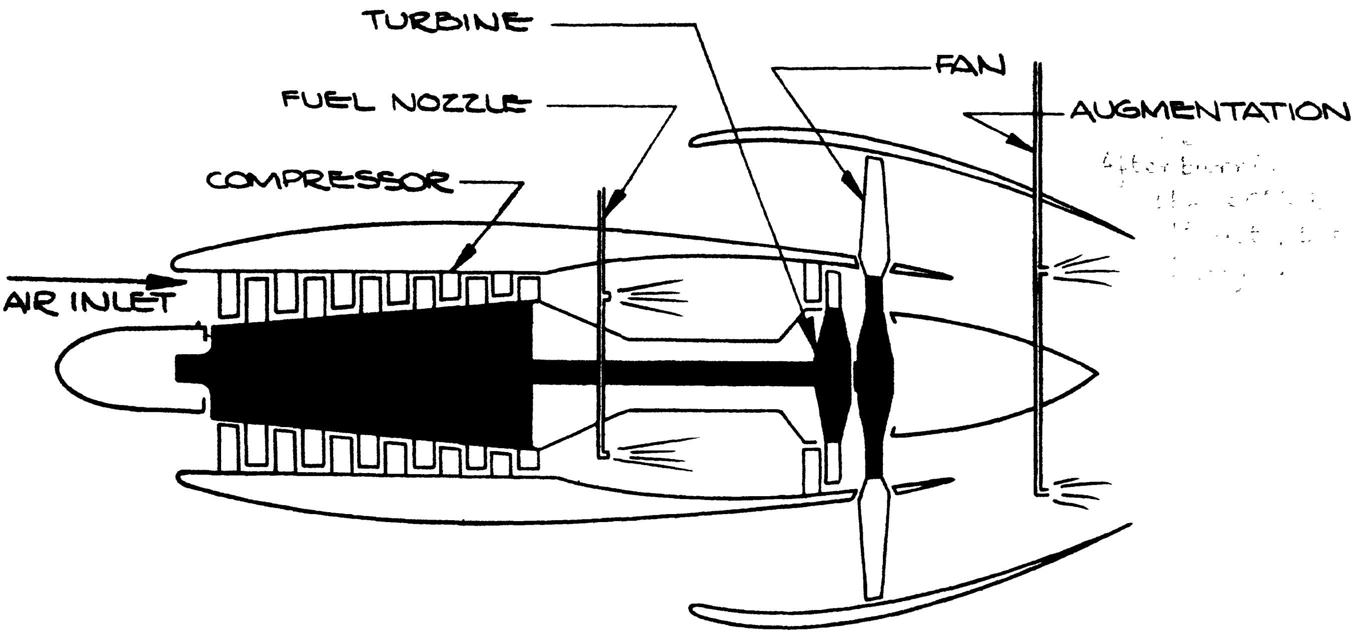
By injecting fuel into the outer periphery of the jet nozzle after the flows have combined, it is also possible



SCHEMATIC SKETCH OF

TURBO-JET

FIG. 7



SCHEMATIC SKETCH OF A

DUCTED FAN

by so-called after-burning or augmentation to increase the thrust output at any speed. The successful design of such a ducted prop or ducted fan turbine-engine might possibly eliminate the necessity for developing the turboprop type engine. In other words, the gap that now exists between the speed at which the conventional propeller efficiency falls off due to tip speed losses and the speed at which the propulsive efficiency of the turbojet approaches that for a propeller may be bridged by the ducted-prop turbojet (see Figure 9). At the same time takeoff efficiency would be improved over that for the turbojet. In all these comparisons it should be noted that the propulsive efficiency comparison represents also the overall efficiency picture since the thermal efficiencies for these engines are approximately constant with speed and of the same magnitude. Since little if any data are available on the ducted-fan type of engine, the following comparisons will apply only for the reciprocating, turboprop, and turbojet engines.

The selection of a suitable power plant to meet range and speed requirements is not only dependent on the thrust and fuel consumption characteristics of the power plants but also on the power plant weight of each type. For example, in Figure 10, assuming a constant structure plus fixed equipment and total gross weight of a series of airplanes, the useful load capabilities of a rocket airplane might be superior to any other type but at a very very

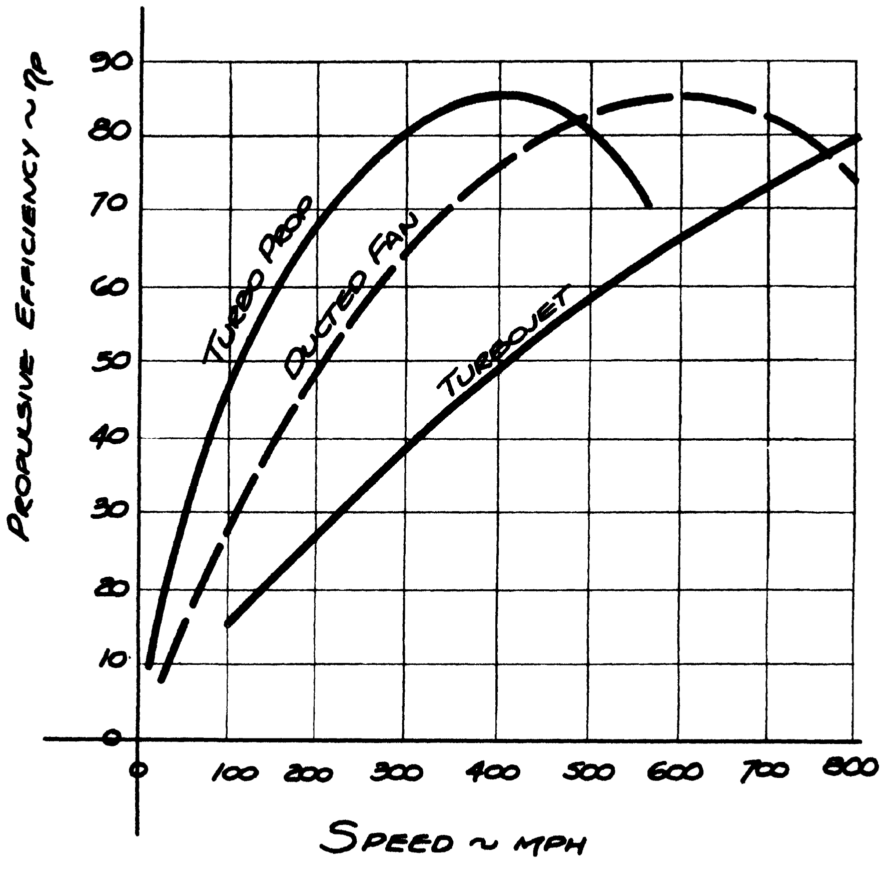
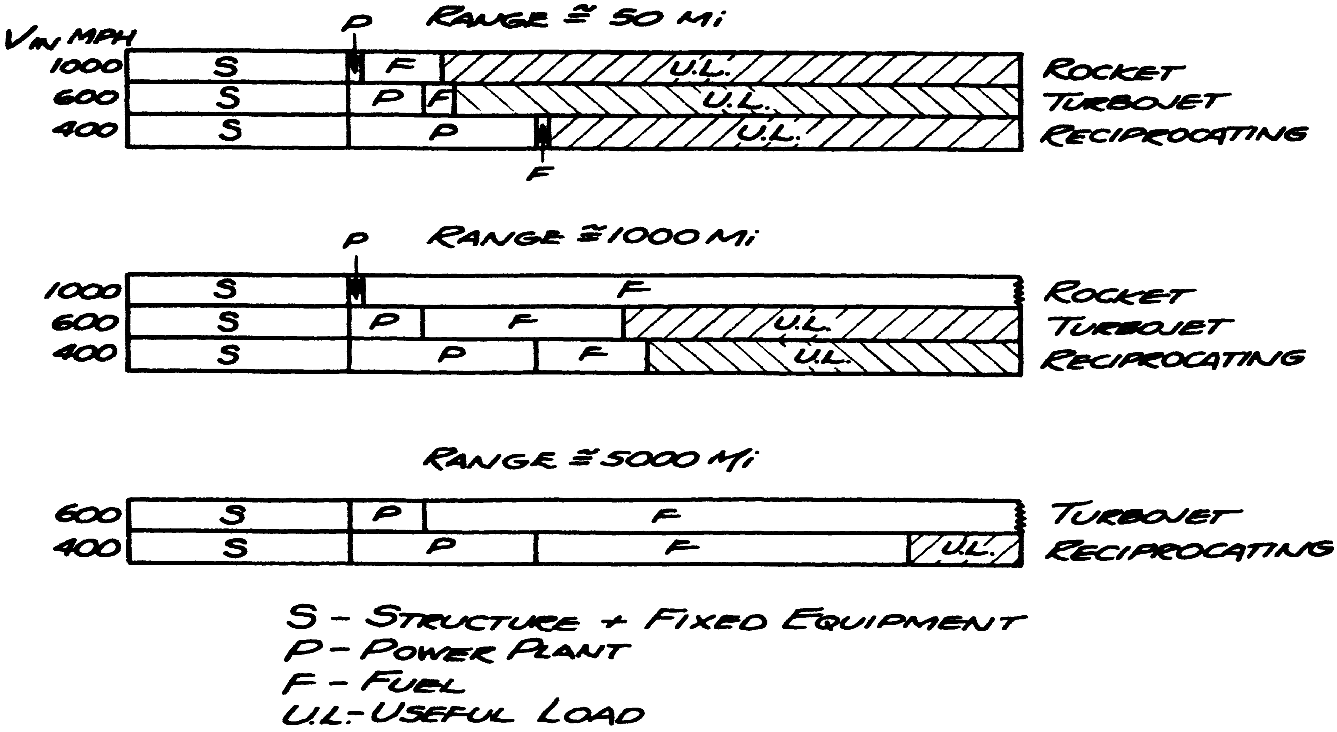

PROPULSIVE EFFICIENCY ~ η_P
90
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
800
SPEED ~ MPH
TURBO PROP
DUCTED FAN
TURBOJET

FIG. 9

short range only, owing to the high fuel consumption characteristics of this type of engine. At a range of 5000 miles the only two engines that have any practical application are the turboprop and the reciprocating, as in this case the initial power plant weight is small in comparison with the fuel weight. At a range of 1000 miles it is possible that a turbojet installation could be superior to the reciprocating engine. Later in this study, a more careful investigation of both power plant and airplane weights and performance will indicate the relative merits of turbojet, turboprop, and reciprocating engine commercial transports for various speeds and ranges.

The availability of engines in each of these three categories is somewhat different. The reciprocating engine is rapidly reaching its limit in total horsepower output and will probably not exceed 5000 hp for takeoff within the next three to five years. By use of turbine feedback devices, the fuel consumption may drop as low as .35 to .4 pounds per brake horsepower per hour within the same period of time.

The outlook for turbopropellers is much better than for reciprocating engined airplanes with reference to maximum power output for takeoff. Theoretical analyses predict power outputs as high as 10,000, but the development of the turboprop engine is still in its infancy and it is doubtful whether these 5,000 to 10,000 shaft horsepower engines will be available before four to six years in the future. The

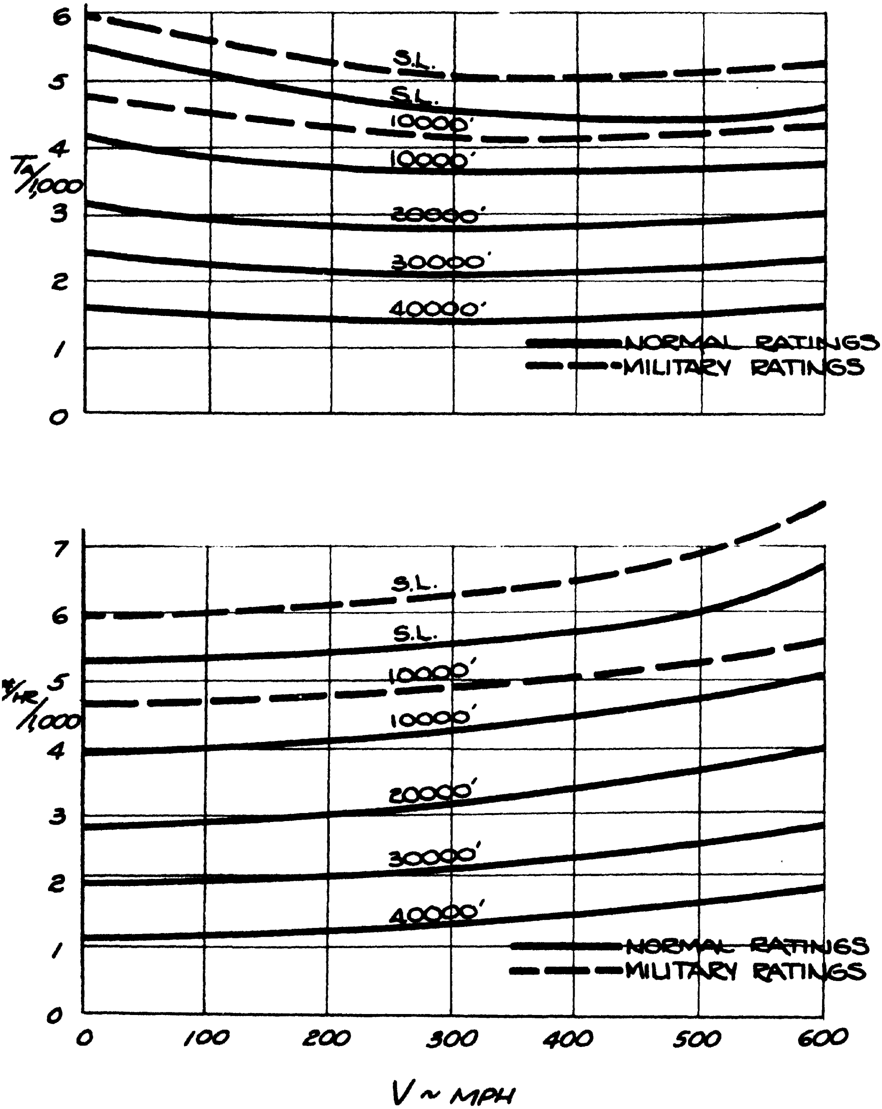


POWER PLANT SELECTION

FIG. 10

English, who are approximately two years ahead of the American development, may have smaller engines available for service in two to three years. The specific fuel consumption in pounds per shaft horsepower per hour may go as low as .4 to .45.

The case for the turbojet engine appears attractive owing to its immediate availability. The Rolls-Royce Company in England has had startling success with the development of the Derwent and Nene centrifugal-compressor turbojet engines. Figure 11 shows the scaled-up performance of the Nene engine for a period from one to two years away. The present rating of the engine for takeoff is 5000 pounds. The reliability of such an engine may also be comparable to the reciprocating engine in relatively the same length of time. At present the time between major overhauls of the Derwent engine is approximately 300 hours as compared to around 750 hours for reciprocating engines. Within the next five years it appears that turbojet engines will be available both in the United States and England with takeoff thrusts as high as 8000 pounds with corresponding fuel consumptions somewhere between .9 and 1 pounds per hour per pound of thrust. Similar to the case of the turboprop, the development in America is lagging approximately one year behind the development in England at the present time. The availability of a large number of engines of this type within the next five years may dictate the use of this type of an engine on jet-propelled commercial transports.

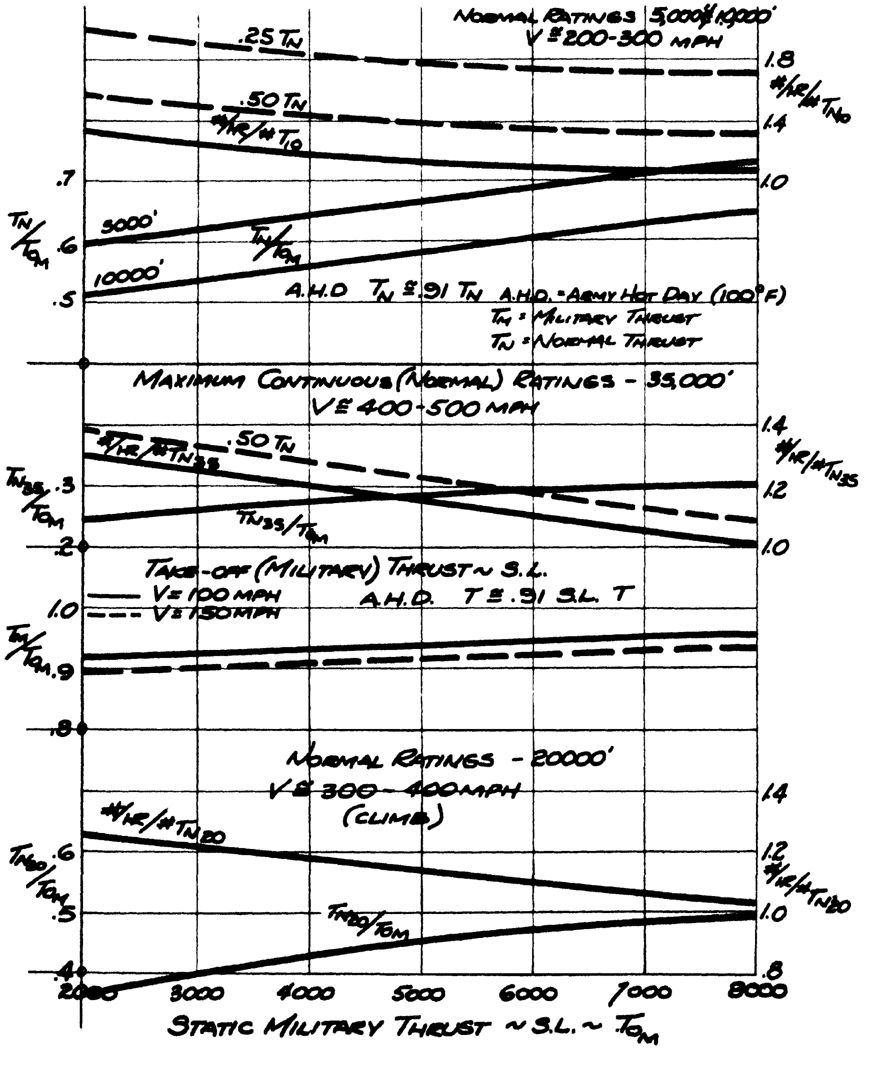


ESTIMATED 'NENE' PERFORMANCE

(Estimated from Rolls Royce Turbojet Power Plant Brochure Published by Taylor Turbine Corporation - August 1946)

Fig. 11

Using as a basis turbojet power plants such as the American Westinghouse 24C, General Electric and Allison I-40, TG-180 and TG-190, and the English Derwent and Nene, Figure 12 represents non-dimensional characteristics of this type of engine. Data are projected one to two years away for maximum static thrust outputs above 5000 pounds. These data and comparable characteristics for the turbo-prop and reciprocating engines are used in the generalized studies presented in Chapter IV.



GENERALIZED TURBOJET ENGINE DATA

FIG. 12

CHAPTER III

BASIC AERODYNAMIC CHARACTERISTICS

By the use of one or a combination of the above power plants, airplanes and guided missles travel at speeds that vary in magnitude through a wide range. These speed regions are commonly divided into subsonic, transonic, and supersonic. To represent these regions, a picture of the variation of drag force, drag coefficient, lift coefficient, and lift to drag ratio with speed or Mach number is shown in Figure 13 for a typical airplane designed for subsonic flight. The drag coefficient, C_D, is non-dimensional and is defined as:

$$C_D = \frac{D}{qS}$$

where

q = dynamic pressure = $\frac{1}{2} \rho v^2 = \frac{\sigma V^2}{391}$

v = velocity in feet per second

V = velocity in miles per hour

ρ = mass density of air in slugs per cubic foot

σ = ratio of any density to that at sea level on a standard day

Similarly, lift coefficient, C_L,

$$C_L = \frac{L}{qS}$$

Drag coefficient and lift coefficient vary with the attitude and shape of an aerodynamic body and with two non-dimensional numbers defined as Reynolds Number, R, and

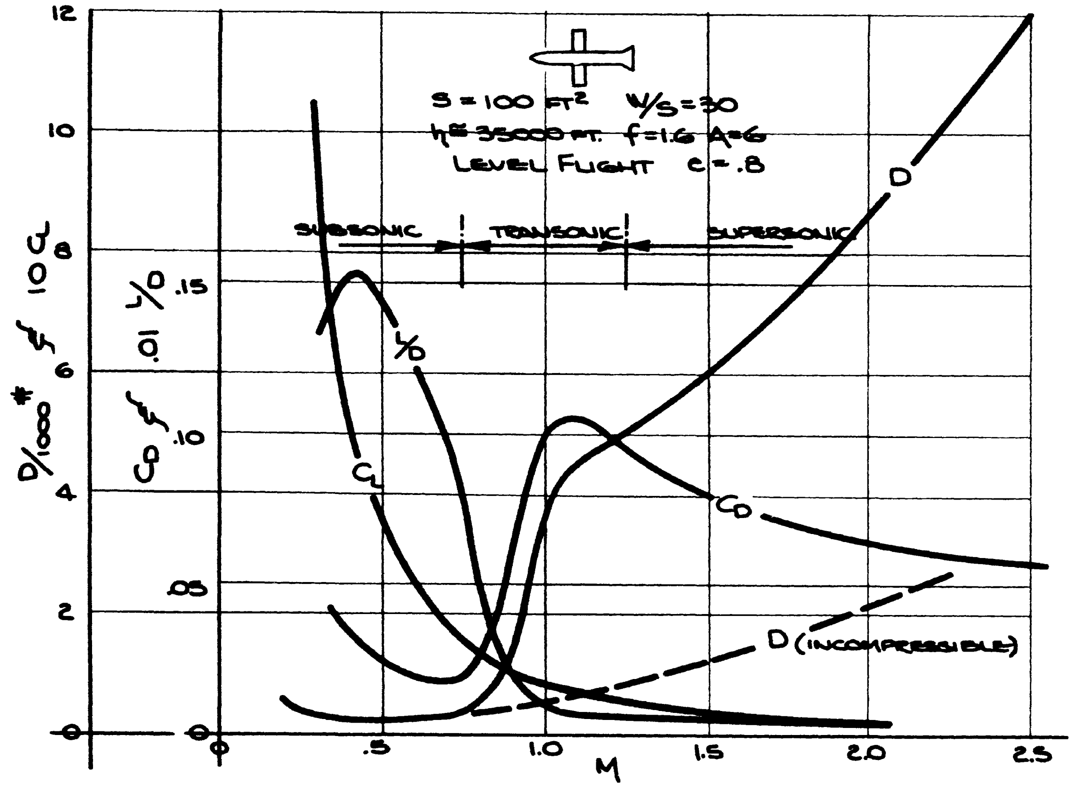
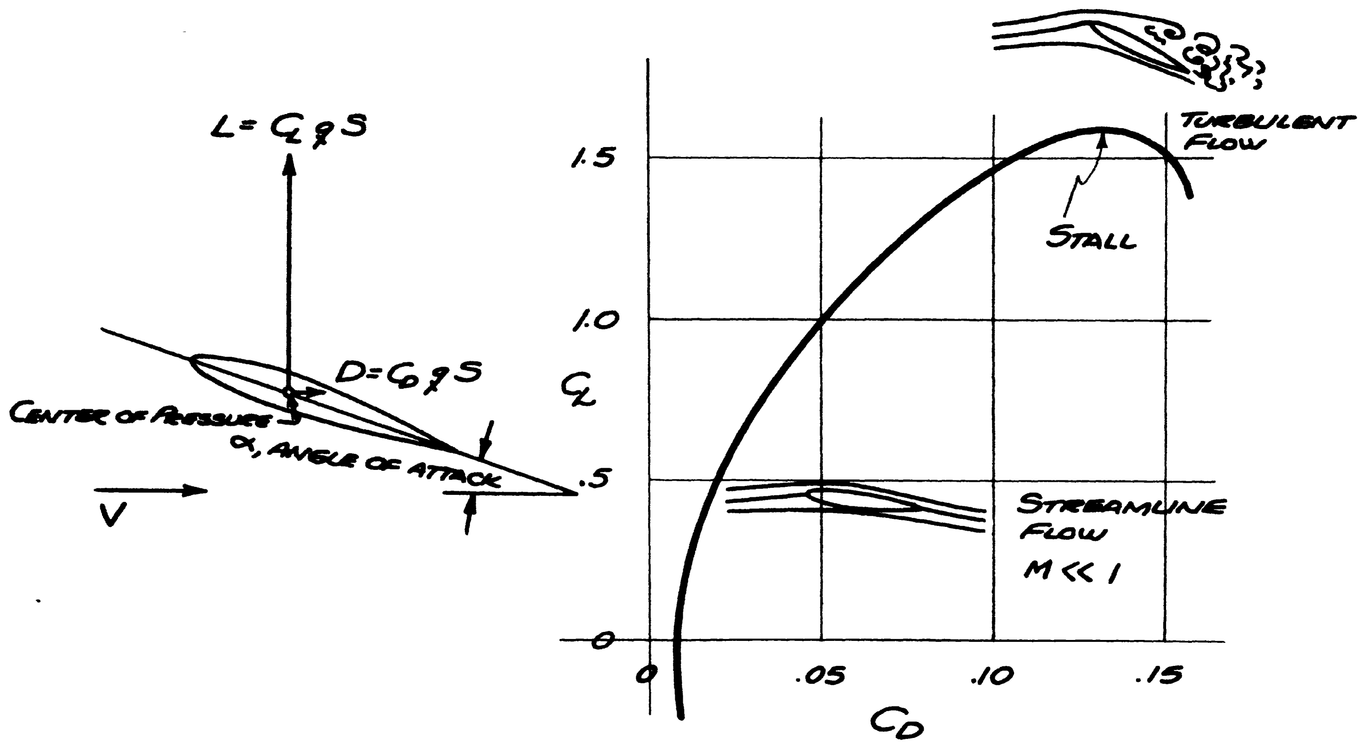


FIG. 13 VARIATION IN LIFT & DRAG WITH MACH NUMBER

and Mach number, M . Within the subsonic region the flow or air over the airplane is essentially incompressible (the density of the air is constant as speed changes), and the C_D remains nearly constant at a given attitude of the airplane or C_L of the wing. There is a slight variation with Reynolds number. Since in uniform level flight $L = W = C_L qS$, both C_L and C_D vary with speed at a given flight altitude. It is convenient, then, to represent the force coefficients of an airplane or a particular aerodynamic shape such as an airfoil in terms of C_L and C_D . (See Figure 14.) For any subsonic speed and size of wing the drag force and lift force may be determined from an airplane polar similar to that for the wing alone represented in this plot.

Within the subsonic region inertia and viscous forces largely determine the behavior of flight. As the speed approaches the speed of sound, the density is no longer constant due to the elastic properties of the air and the consequent compression of the air as it approaches the body. It is noted in Figure 13 that the C_D varies rapidly with Mach number, M , as the latter approaches and exceeds a value of unity. At or near a Mach number of unity a compression normal shock wave is set up in front of the body. Behind this wave the flow is very turbulent and represents a loss in energy or an increase in drag coefficient of the body. As the Mach number increases above unity the shock wave attaches itself to the nose of the body and trails back on either side forming an oblique wave. Since the



AIRFOIL NOTATION & TYPICAL POLAR

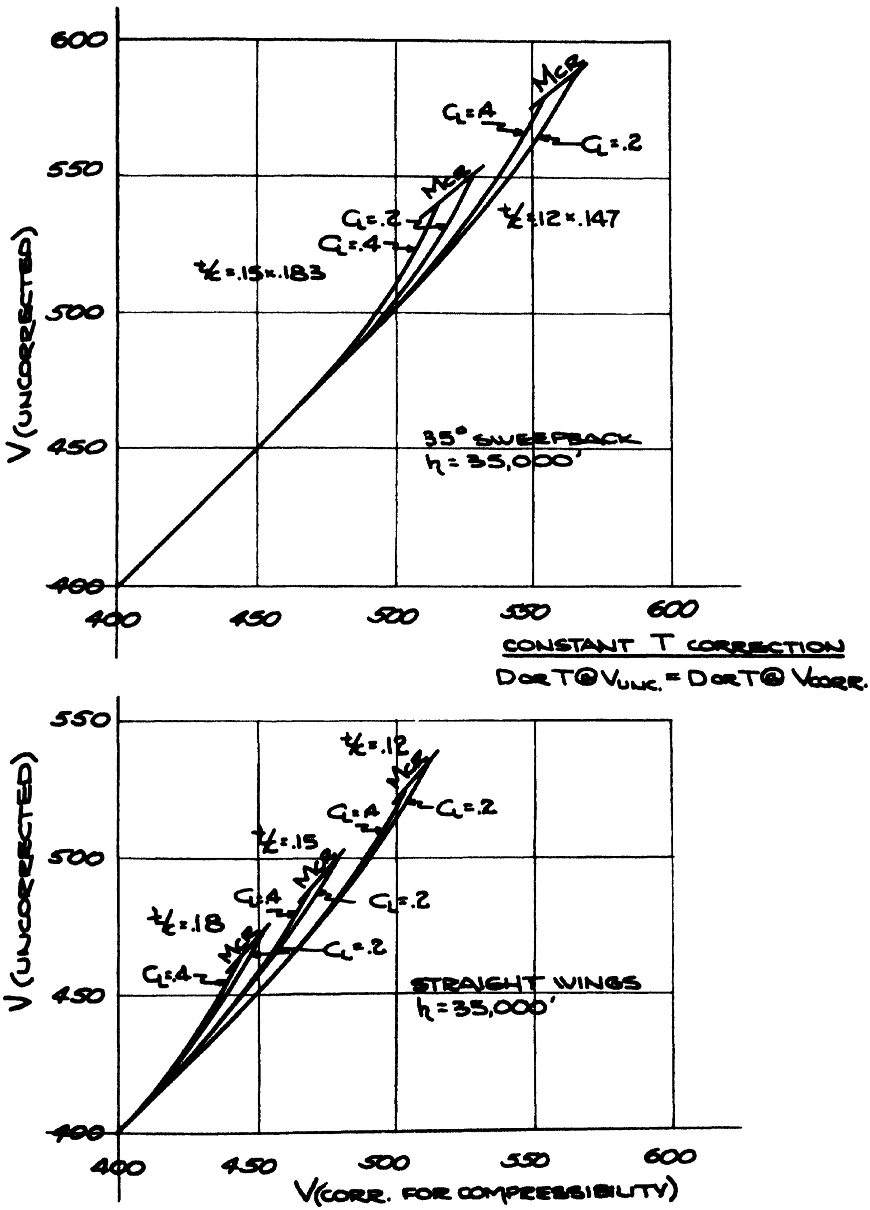
FIG. 14

energy loss in this type of wave is less than in the normal wave, the drag coefficient decreases. Minor compression and expansion waves may also be propagated on the body where the flow of air changes direction. Mach number is defined as $M = \frac{V}{a}$ where a is the speed of sound or rate of propagation of pressure waves in any fluid medium. In air, the speed of sound varies from approximately 761 mph at sea level to 662 mph at 35,000 ft altitude. The speed of sound varies with the absolute temperature of the air and follows the variation of the latter with change in altitude. It is also noted from Figure 13 that the lift-to-drag ratio decreases rapidly at speeds above the subsonic region. Since this ratio is one of the three factors that affects range performance, the design of an airplane to fly long distances at very high speeds is very difficult.

Since the subject under discussion deals with flight in the subsonic region or before serious compressibility difficulties are encountered, it is necessary now to examine some of the aerodynamic properties of the airplane that affect performance in this speed region. The supersonic commercial transport of tomorrow is still very much of a conjecture, and no further remarks will be made in this direction. It is obvious from Figure 13 that practical limitations on available thrust dictate flight below the critical Mach number of an airplane wing (corresponds to the Mach number at which the drag begins to

increase rapidly. For cruising speeds of 500 to 525 mph at 35,000 ft (Mach number = .75 to .8) the thrust requirement or drag for a jet transport with a straight wing is considerably higher than that for a sweptback wing. A set of speed correction curves for a typical airplane using straight and swept wings is presented in Figure 15. For a swept wing (tested two-dimensionally) the component of velocity normal to the peak-pressure chord line determines the critical velocity or Mach number. The component parallel to this line affects skin-friction drag but not pressure drag. At or slightly above the M_{cr} of the wing, the rapid change in lift and drag forces and the movement of the center of pressure cause serious stability and control problems. This, accompanied by local vibrations on those moveable parts of the airplane where shock waves form, make flight at these speeds extremely hazardous. For commercial operation the scheduled cruising speed of a transport should be lower than the critical speed by a margin of approximately 50 mph in order that reasonable safety can be assured if an inadvertent increase in speed is encountered.

The drag on an airplane may usually be divided into two parts, parasite drag (that part due to friction and pressure) and induced drag (that part associated with lift or keeping the airplane aloft).



SPEED CORRECTION CHARTS

Fig. 15

Drag = parasite drag + induced drag

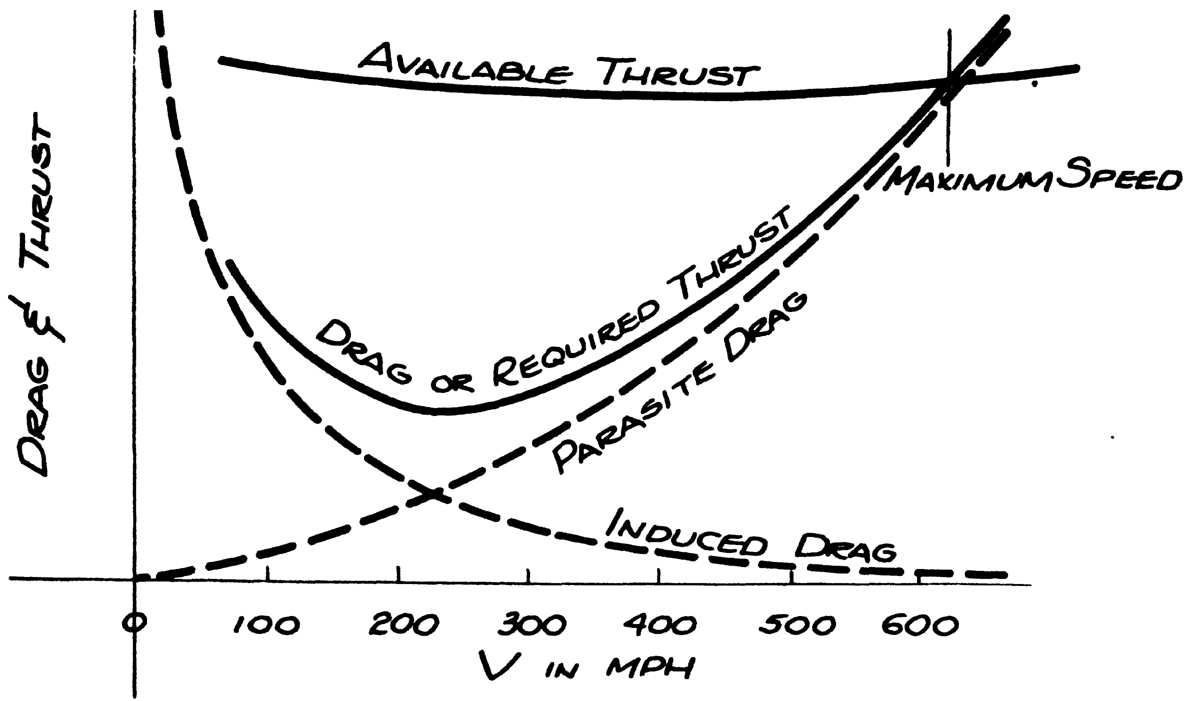
$$D = fq + \frac{W^2}{\pi\, q\, b^2 e}$$

$$q = \frac{1}{2}\rho\, V^2 = \frac{\sigma V^2}{391}$$

Design variables:

W, f, b, e and σ

Efficiency factor, e, accounts for the variation of parasite drag with angle of attack and with the deviation of the wing downwash from that required for minimum induced drag. Equivalent parasite area, f, represents the minimum parasite drag of the airplane. In Figure 16 is presented a graphic breakdown of induced and parasite drag. As far as the airplane is concerned, then, any change in W, b, e, and f, will affect the drag at any given speed. Of these variables, f and W can be controlled somewhat by both the designer and procurer, and lack of control often results in serious performance losses. Span is usually fixed by the design requirements and is usually a compromise between structural and aerodynamic design trends. A low ratio of W/b is desirable if climb performance requirements as dictated by the Civil Aeronautics Authority are critical limitations. Altitude, σ, of course, affects performance but is not an airplane characteristic and as such cannot be controlled. Equivalent parasite area, f, is dependent on the cleanness as well as size of the airplane and may seriously



AVAILABLE & REQUIRED THRUST

Fig. 16

affect the cruising performance of high speed airplanes. For example, suppose excrescences such as turrets, blisters, rough surfaces, etc. were to increase f by 10 per cent on a given series of airplanes, from Figure 17 it can be seen that the loss in cruising speed becomes very serious for high-speed airplanes like the B-47. For constant power available, the speed loss for the C-47, B-17 and B-29 amounts to about 3 per cent. For constant thrust, the loss on the B-47 is about 4.3 per cent. For turbojet airplanes the high loss in mph is due not only to the high speed but also to the fact that for a constant cruising thrust available, the actual power available is less as the speed is reduced. It is also important to note that the addition of the same radome, for example, on a B-47 reduces the cruising or high speed even to a greater extent than that of the B-29 because the percentage reduction in f or parasite drag is greater for the cleaner airplane. A similar analogy may be used for high-speed commercial transports.

The weight change of an airplane has even more far-reaching effects on performance than change in parasite drag. All performance items suffer by an increase in weight. As far as speed is concerned, an increment change in weight reduces the cruising speed by a greater amount than high speed. This is because induced drag is a greater proportion of the total drag at low speeds than at high speeds (see Figure 16).

Rate of climb is materially decreased because of an increase in airplane drag and increase in weight. Takeoff and landing distances are materially affected as shown by the variables affecting these items in Figure 18.

Range is the performance item that takes the greatest penalty by an increase in weight. The following letter written by the Boeing Aircraft Company to the Office of the Air Inspector on August 30, 1946, serves as an illustration.

> During your recent visit to our plant, you requested us to furnish you a list showing the difference between the guaranteed and actual weights of Government Furnished Equipment for some particular airplane and the actual effects these overweights had on the performance of that airplane. You desired these data in connection with a study you were making on weight control of Government Furnished Equipment.
>
> The enclosures herewith are weight data for the XB-29 airplane. This airplane is the prototype of the B-29 Super-Fortress and was selected for your example because the weight data were readily available. The overweight effects on performance which we will list below are assumptions computed by our Aerodynamics Department. However, for the purposes of your study, we feel that you can safely say that the performance of the airplane would have been that much better if the weights of the GFE had remained within the guarantees.
>
> The GFE items had a total overweight of 1510 pounds and affected the performance as follows:
>
> 1. Long range operations are usually based on a maximum allowable take-off weight which is dependent upon airplane performance during and immediately after takeoff. In this case, if the weight empty is increased 1510 lbs and it is not desired to reduce the bomb load, fuel and oil must be reduced by 1510 lbs. This would reduce the maximum range for a 2000-lb bomb load by about 285 statute miles.
>
> 2. In the case where takeoff weight is not critical and the 1510 lbs increase in weight empty can be added to the takeoff weight to maintain the same

EFFECT OF CHANGE IN PARASITE DRAG ON SPEED

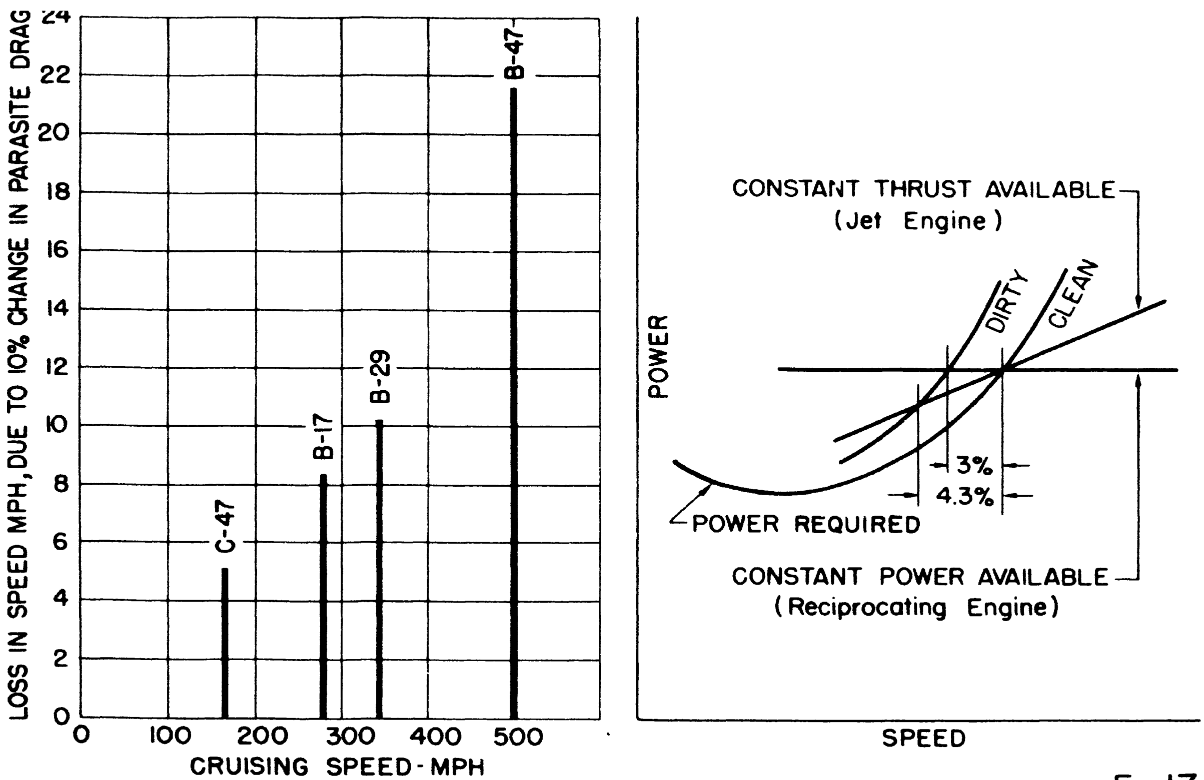


FIG. 17

fuel, oil, and bomb loads, the range would be reduced by as much as 150 miles for a long mission.

3. The increased weight would reduce the 4-engine rate of climb approximately 25 ft per minute.

4. Four-engine ceilings would be reduced about 600 ft., three-engine ceilings 850 ft., and two-engine ceilings 1050 ft for the increase in weight.

5. Takeoff distance would be increased approximately 150 ft for a 1510-lb increase in takeoff weight.

These are the effects of overweights only. If the overweight items are also not as clean aerodynamically as originally estimated, further losses would result.

The effect on range is illustrated graphically in Figure 19. In this figure the miles of range per pound of fuel consumed is plotted versus weight. The area under the curve represents range. It is important to note that the airplane goes about twice as far per pound of fuel in the light condition as compared to the fully-loaded condition. This difference is the result of the effect of W on the drag of the airplane resulting in less thrust or power requirement from the engine or less fuel consumed.

In case (1) of the reference letter the loss in range is illustrated by the area under the miles per pound curve at the light weight condition. In case (2) some of this loss is recovered by takeoff at a higher gross weight (see Figure 19).

Figure 19 illustrates the increase in takeoff weight required if the range and bomb load are to remain the same as with no overweight items. This means that for every pound of overweight that affects the weight empty

TAKE-OFF CHART

T = TOTAL STATIC THRUST

P = TOTAL BRAKE HORSE POWER (FOR TURBOPROP USE EQUIVALENT SHAFT HORSE POWER AT TAKE-OFF SPEED)

$C_{L_{T.O.}}$ = TAKE-OFF LIFT COEFFICIENT

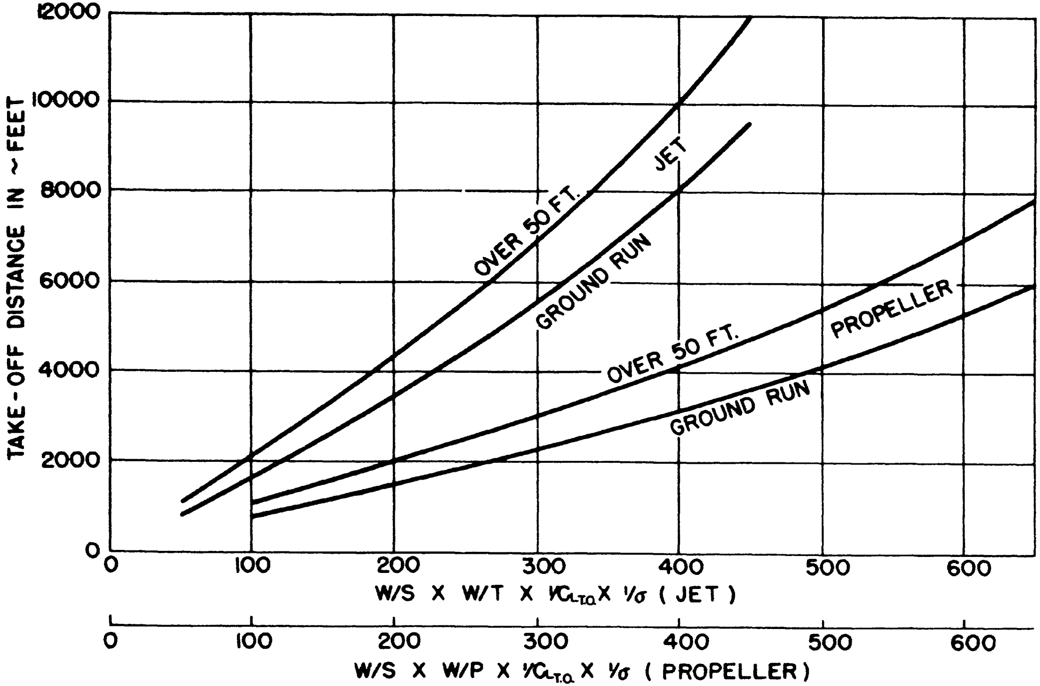


FIG. 18

of the airplane approximately one pound of additional fuel is required, resulting in about two pounds increase in takeoff weight. On long range missions this effect is extremely important, as the difference in initial and final weights is great. On the B-36, for example, or a trans-ocean airliner, a one-pound increase in weight empty would require approximately two pounds of fuel to keep the maximum range the same. In the design of a successful long range airplane, the designer must take particular caution to keep items of structural, fixed equipment, and power plant weights to a minimum.

In the following tabulation and in Figure 20 is presented representative weight, parasite drag, and direct operating cost data for turbojet, turboprop, and reciprocating engine commercial airplanes. These data are used as the basis for the generalized studies presented in Chapter IV. A more detailed examination of performance requirements for commercial transports will indicate the relative importance of some of the foregoing airplane parameters as they affect the design of jet transports.

1. WEIGHT BREAKDOWN

Basic Structure Weight Equation

$$W_S = .21W + \frac{2W^2}{10^7} + 4.2S \text{ (for } t/c = .15 \ A = 10\text{)}$$

W_S for other values of t/c, A, and Sweepback

(See Figure 20)

Fixed Equipment

$$W_{FE} = .06W + 100N_P$$

Passengers + Baggage

$$W_{P+B} = 200\ N_p$$

Cargo

$$W_C = .15 \times 200\ N_p = 30\ N_p$$

Crew + Stewardess

$$W_{C+S} = 200\ N_C + 8\ N_p$$

Service Equipment

$$W_{SE} = 15\ N_p$$

Fuel

$$W_F = W_{F_{Climb}} + W_{F_{Maneuver}} + W_{F_{Cruise}} + W_{F_{Reserve}}$$

Power Plant

$Wpp \sim$ type of unit

a. Turbojet

$$Wpp = 3.4\ N_E\ (T_{O_M})^{3/4}$$

b. Turboprop

$$Wpp = 6.8\ N_E\ (P_{O_M})^{.76}$$

c. Reciprocating

$$Wpp = 1.9\ N_E\ P_{O_M}$$

$$\text{Total } W = .21W + \frac{2W^2}{10^7} + 4.2S + Wpp + 353\ N_p + .06W + 200 + W_F$$

Final Equation

$$W = .27W + \frac{2W^2}{10^7} + 4.2S + Wpp + 353\ N_p + 200 + W_F$$

2. EQUIVALENT PARASITE AREA BUILDUP

$$f = f_{Fuselage} + f_{Wing + Tail} + f_{Nacelle}$$

$$f_{Fus.} = 2 + .25\ Np$$

$$f_{Wing} = .0065S$$

$$f^{Take\text{-}off}_{Flaps} = .02S$$

$$f_{Tail} = .008\ S_{Tail} = .0024\ S$$

$$f_{W+T} = .009S$$

$$f_{Landing\ Gear} = f_{Clean\ Airplane}$$

$$f_{NAC} \sim T_{0_M}\ P_{0_M}$$

Turbojet

$$f_{NAC} = .003\ N_E\ (T_{0_M})^{2/3}$$

$$f_{NAC}\ (\text{One Eng. Out}) = .01\ (T_{0_M})^{2/3}$$

(Drag due to dead engine)

Turboprop

$$f_{NAC} = .0039\ N_E\ (P_{0_M})^{.42}$$

$$f_{NAC}\ (\text{One Eng. Out}) = .15\ (P_{0_M})^{.42}$$

(Drag due to dead engine and windmilling propeller)

Reciprocating

$$f_{NAC} = .04\ N_E\ (P_{0_M})^{.50}$$

$$f_{NAC}\ (\text{One Eng. Out}) = .05f$$

(Drag due to dead engine and windmilling propeller)

$$\therefore\ f = 2.0 + .25\ N_p + .009S + f_{NAC} \qquad \text{Clean airplane}$$

3. DIRECT OPERATING COST BREAKDOWN

$$\text{¢/Ton-mile} = (\text{¢/Ton-mile})_{Fuel} + (\text{¢/Ton-mile})_{Eng.} + (\text{¢/Ton-mile})_{Airframe} + (\text{¢/Ton-mile})_{Insurance} + (\text{¢/Ton-mile})_{Crew\ and\ Stew.}$$

$(\text{¢/Ton-mile})_{Fuel} \sim$ Type of Unit (Diff. Fuels Used)

Turbojet
Turboprop $\quad (\text{¢/T-M})_F = \dfrac{1.91\,(W_{F_{Climb}} + W_{F_{Man.+CR}})}{R \times P}$

where R = Range and P = Payload in Tons = $.115N_p$

Reciprocating $\quad (\text{¢/T.M.})_F = \dfrac{2.67\,W_{F_{Cl+Man+Cr}}}{R \times P}$

$(\text{¢Ton-mile})_{Eng.} \dfrac{N_E(.335\,W_{Eng} + 307)}{V_B P}$ Turbojet Turboprop

$(\text{¢Ton-mile})_{Eng.} \dfrac{N_E(.300\,W_{Eng} + 307)}{V_B P}$ Reciprocating

$$V_B = \text{Block Speed} = \frac{\text{Range}}{t_{Climb} + t_{Cruise} + t_{Maneuver}}$$

t = time in hours

$$(\text{¢/Ton-mile})_{Airf.} = \frac{.117\,W_{Airframe}}{V_B P}$$

$$(\text{¢/Ton-mile})_{Ins.} = \frac{.0296\,W_{Empty}}{V_B P}$$

$$(\text{¢/Ton-mile})_{Crew+Stew.} = \frac{998 + 4.8\,V_B}{V_B \times P}$$

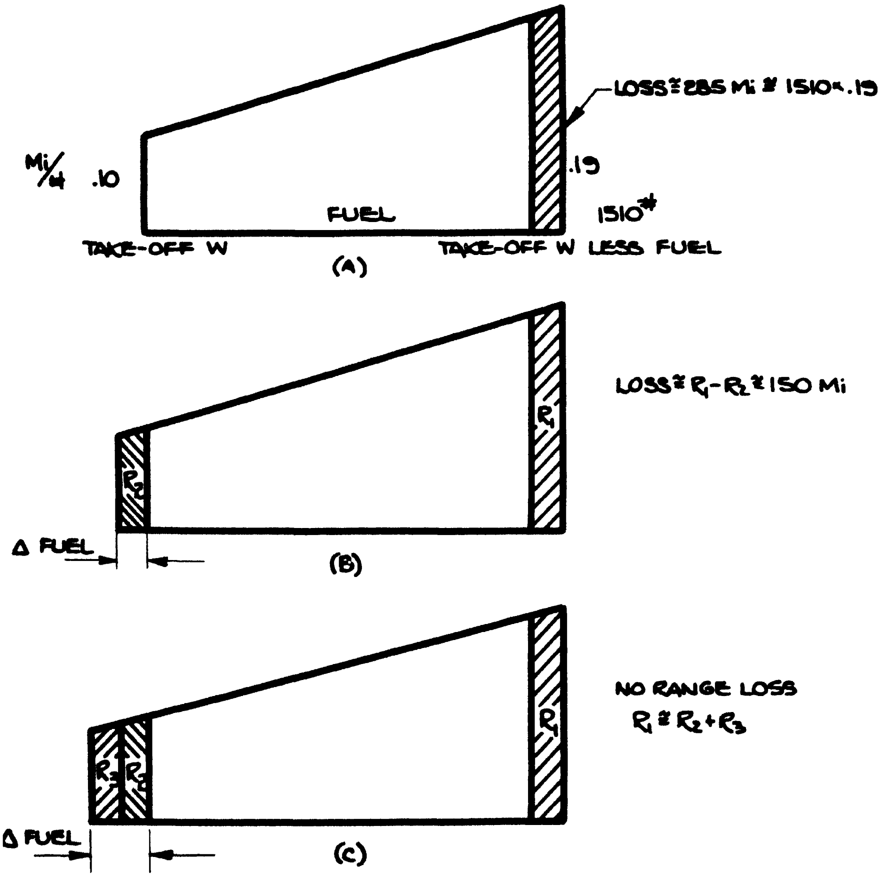
(¢/Ton-mile) = Total Operating Cost

$$¢/\text{Ton-mile} = (¢/\text{Ton-mile})_{Fuel} + (¢/\text{Ton-mile})_{Eng} + \frac{.117\ W_A + .0296\ W_E + 998}{V_B P} + \frac{4.93}{P}$$

For additional (over 2) pilot add $\frac{233 + 1.95\ V_B}{V_B P}$

For additional stewardess (over 1) add $\frac{95 + .6\ V_B}{V_B P}$

W	=	Gross Weight in pounds
W_F	=	Weight of Fuel
N_E	=	Number of Engines
W_{Eng}	=	Weight of Engine
W_A	=	Weight of Airframe
W_E	=	Weight Empty
R	=	Range in miles
P	=	Payload in tons
S	=	Wing Area in square feet
T_{O_M}, P_{O_M}	=	Maximum Sea Level Static Thrust or Power
N_p	=	Number of Passengers
f	=	Equivalent Parasite Area in square feet



EFFECT OF WEIGHT INCREASE ON RANGE

FIG. 19

CHAPTER IV

THE CASE FOR THE TURBOJET COMMERCIAL TRANSPORT

In an attempt to evaluate the relative merits of the reciprocating engine, turboprop, and turbojet transports, a number of generalized airplane studies are set up to show the effect of airplane, engine, and performance variables. Airplane and engine characteristics are formulated in generalized terms so that the effect of each variable can be investigated separately with consistent results. Listed below are some of the variables affecting the performance and weight of these transports:

(1) Range.

(2) Wing loading (as affected by field length and $C_{L_{Max}}$).

(3) Thrust or power loading.

(4) Effect of wing sweep-back on cruising speed and passenger comfort.

(5) Number of passengers.

(6) Assisted takeoff.

(7) Number of engines.

(8) Aspect ratio and thickness ratio.

(9) Cruising altitude.

Each airplane is designed for minimum direct operating cost. This corresponds to the highest possible wing loading consistent with C.A.A. landing field requirements and the highest possible thrust or power loading consistent

with refused takeoff, climb, cruising, or ceiling requirements. Landing weight is assumed to equal the gross weight minus one-half the fuel for climb, maneuver, and cruise.

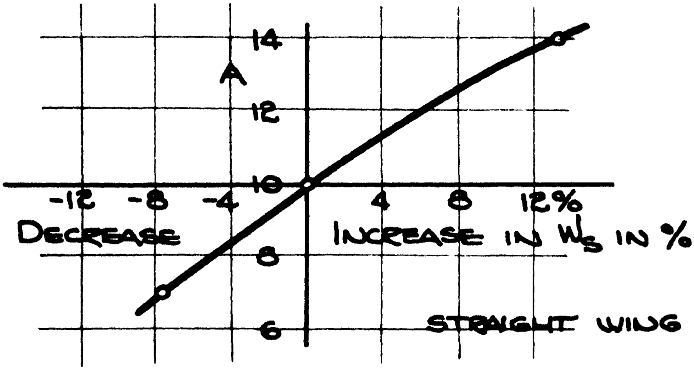
Figure 21 shows a typical generalized design chart for a swept-wing turbojet airplane in terms of thrust loading, W/To_M, and wing loading, W/S. W is defined as maximum gross weight and To_M as maximum static takeoff thrust. On this chart are presented the performance requirements dictating the design W/S and W/To_M based on data from a number of generalized airplane studies. Assuming a given ground deceleration of approximately 7 ft/sec^2, the landing field distance is a function of W/S. For a given field length requirement, then, the maximum design W/To_M can be determined by following up a constant landing field length line until a critical performance cut-off is reached. Engine-out takeoff, climb, and ceiling requirements are based on thrusts obtainable under temperature conditions above those for a standard day. Constant cruising speed lines represent maximum speeds at 35,000 feet altitude. If field length is a variable, an optimum set of the parameters, W/S and W/To_M, would occur at the intersection of a critical climb condition $(.035\ V_{s1}{}^2)$ and the maximum speed desired. This speed should be somewhat less than the critical speed of the airplane.

In the generalized studies that follow, a given field length, passenger capacity, and range are established. The weight and size of an airplane are determined from

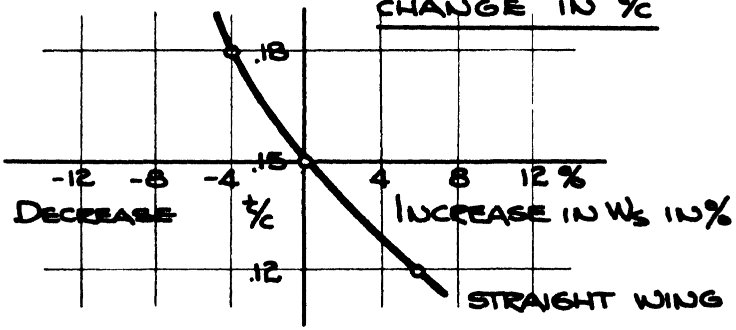
$$W_{STRUCTURE} = .21W + \frac{2W^2}{10^7} + 4.2S$$

$(t/c = .15 \quad A = 10)$

CHANGE IN A



CHANGE IN t/c



FOR $\beta = 35°$ SWEEPBACK

CALC. THE SPAN ALONG THE 1/4 CHORD LINE.
CALC. THE A USING THIS SPAN. $A = b^2/S$
CALC. THE t/c ⊥ TO THE 1/4 CHORD LINE.
USING THE TWO CURVES ABOVE, THE ΔW_S (CHG. IN THE STRUCTURAL WT. FROM A STR. WING AIRP. WITH $A=10$, $t/c=.15$) MAY BE FOUND. ADD 4% TO ACCOUNT FOR THE INCREASE IN THE STRUCTURAL SUPPORT.

FIG. 20

generalized equations set up in terms of W/S and W/To_M. The cruising speed at 35,000 ft is then determined by the engine size required for the critical climb or takeoff requirement. Equivalent parasite area, f , is also set up in terms of W/S and W/To_M and the known variables. A typical set of generalized equations for some of the designs are presented at the end of Chapter III. The weight equation is modified depending on the wing characteristics as presented in Figure 20. The equivalent parasite area is for a clean airplane and is modified depending on the landing gear position, flap position, and engine-out conditions. Generalized engine data are taken from Figure 12.

Each airplane is cruised at or near speed for maximum range. In the case of the turbojet and turboprop it is found that cruising at maximum continuous thrust or power is desirable. During climb each airplane is flown at or near the speed for maximum rate of climb. Reserve fuel is carried for two hundred miles plus three quarters of an hour at 10,000 feet altitude at speeds for minimum fuel consumption. A cruising altitude of 35,000 feet is assumed.

Direct operating costs are based on slightly modified A.T.A. formulas. The cost of kerosene as a fuel is assumed at 13 cents a gallon and that for gasoline at 16 cents a gallon. Major overhauls on jet engines are assumed every five hundred hours. Standard wing sections are assumed varying in thickness ratio from twelve to eighteen percent. A taper ratio of .4 is used throughout; an aspect ratio of

10 is used for most studies. Sixty per cent span fowler-type flaps are assumed producing a $C_{L_{Max.}}$ of 2.8 and a $C_{L_{Takeoff}}$ of 2.2 for straight-wing designs and 2.25 and 1.7 for swept-wing designs.

For any desired field length, passenger capacity, and range, the weight equation can be balanced by successive approximation. From the landing field length desired the maximum allowable wing loading can be established, and from the performance requirements the maximum allowable thrust loading can be established. By computing the weight of fuel for climb, maneuver, cruise, and reserve conditions, the gross weight of the airplane can be determined, which in turn will permit the evaluation of the direct operating costs in cents per ton-mile. Since in all studies range is found to be one of the most important variables, weight, block speed and direct operating costs are plotted against this variable in Figures 22,23, and 24. Each point on these curves represents an optimum airplane designed at that particular range. These data indicate that the optimum design range for a minimum operating cost is the lowest for the turbojet and highest for the reciprocating engine airplane. But, turboprop and reciprocating engine airplanes can be designed through a wide band of ranges with little effect on the direct operating cost, whereas the turbojet suffers appreciably for any range very far away from the optimum. Turbojet designs are space limited for wing fuel capacity at approximately 1500 miles range. The

other two types have no wing fuel-space limits for any practical range requirement up to approximately 5000 miles.

For a fifteen per cent wing section, a cruising speed of 450 miles an hour can be obtained by either the turboprop or turbojet. This speed is approximately forty to fifty miles per hour below the critical speed of a straight-wing airplane. At this cruising speed it is seen that the cost of the turboprop is considerably lower than that for the turbojet.

By the use of a swept wing configuration either type can be cruised at approximately 525 miles per hour still maintaining the same margin of forty to fifty miles per hour between cruising speed and critical speed. At this speed the turbojet, designed near its optimum range is cheaper to operate than the turboprop. A propeller designed to operate at seventy to eighty per cent efficiency for this speed may be available in five years.

The operating cost of the reciprocating engine airplane is comparable for most ranges to the turboprop airplane but the block speed is comparatively lower. At higher values of cruising speed the cost of this type of airplane rises sharply due either to excessive weight of engine installation or excessive fuel consumption caused by cruising above seventy per cent normal brake h.p.

Figure 25 is derived from a cross-plot of the data presented in Figures 23 and 24 and represents the effect of block speed on direct operating cost for a range of 1000 miles. From this chart it is concluded that higher

GENERALIZED DESIGN CHART

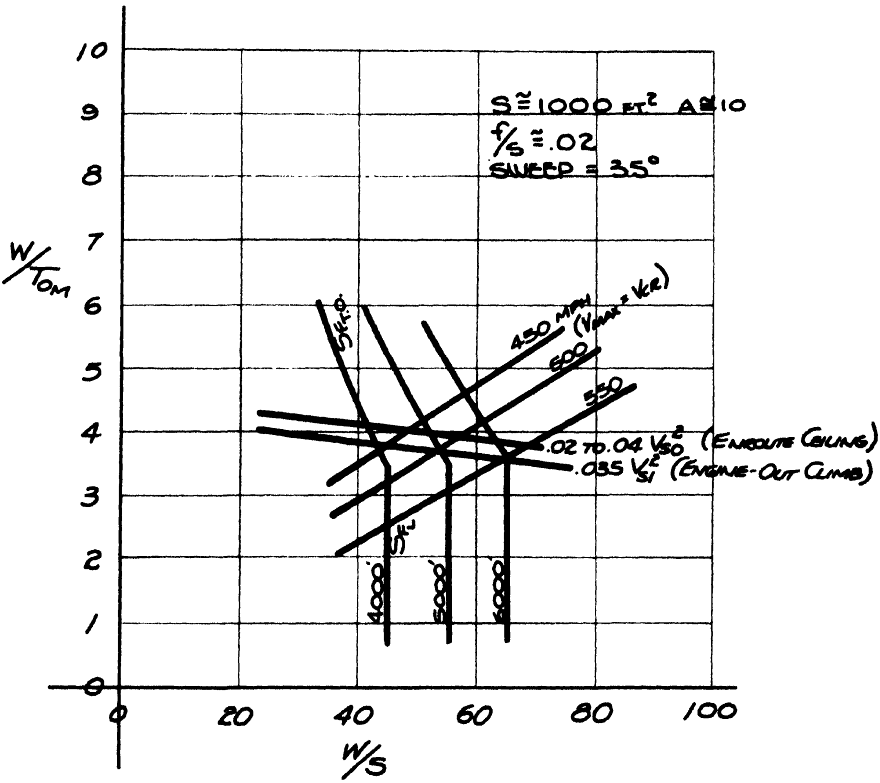
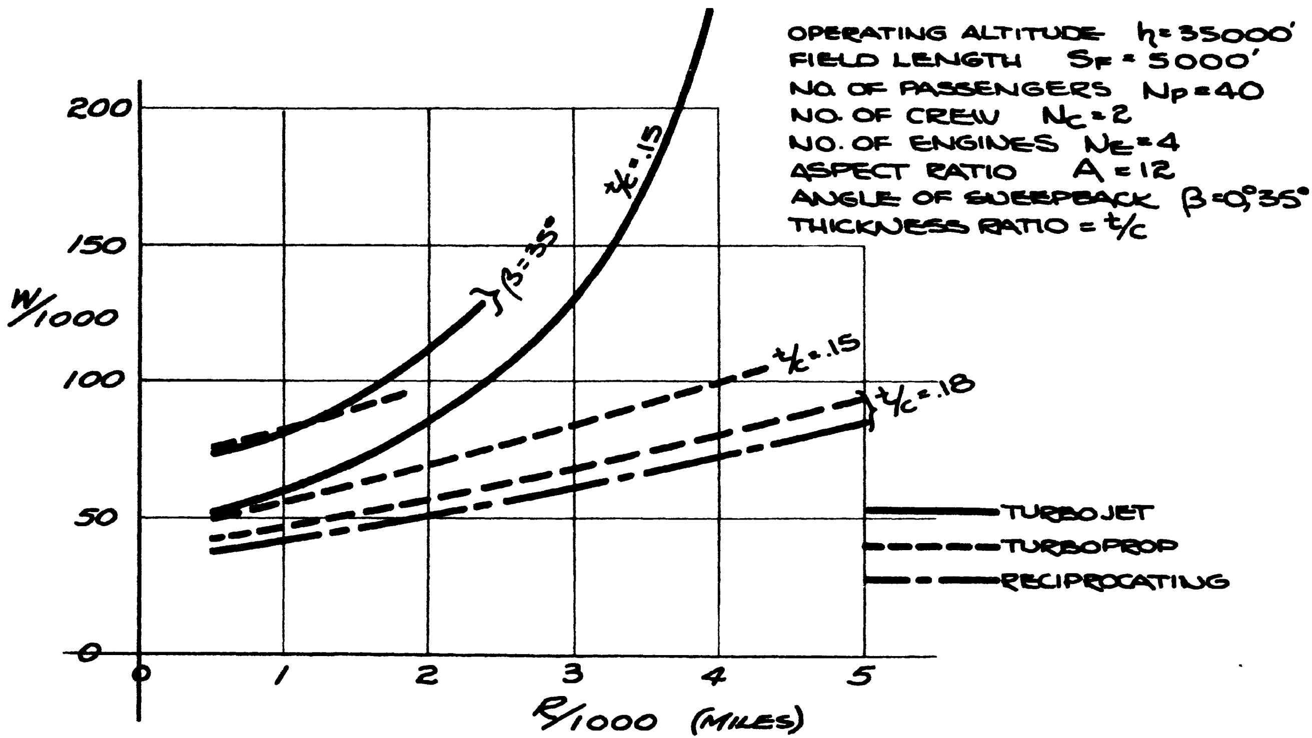
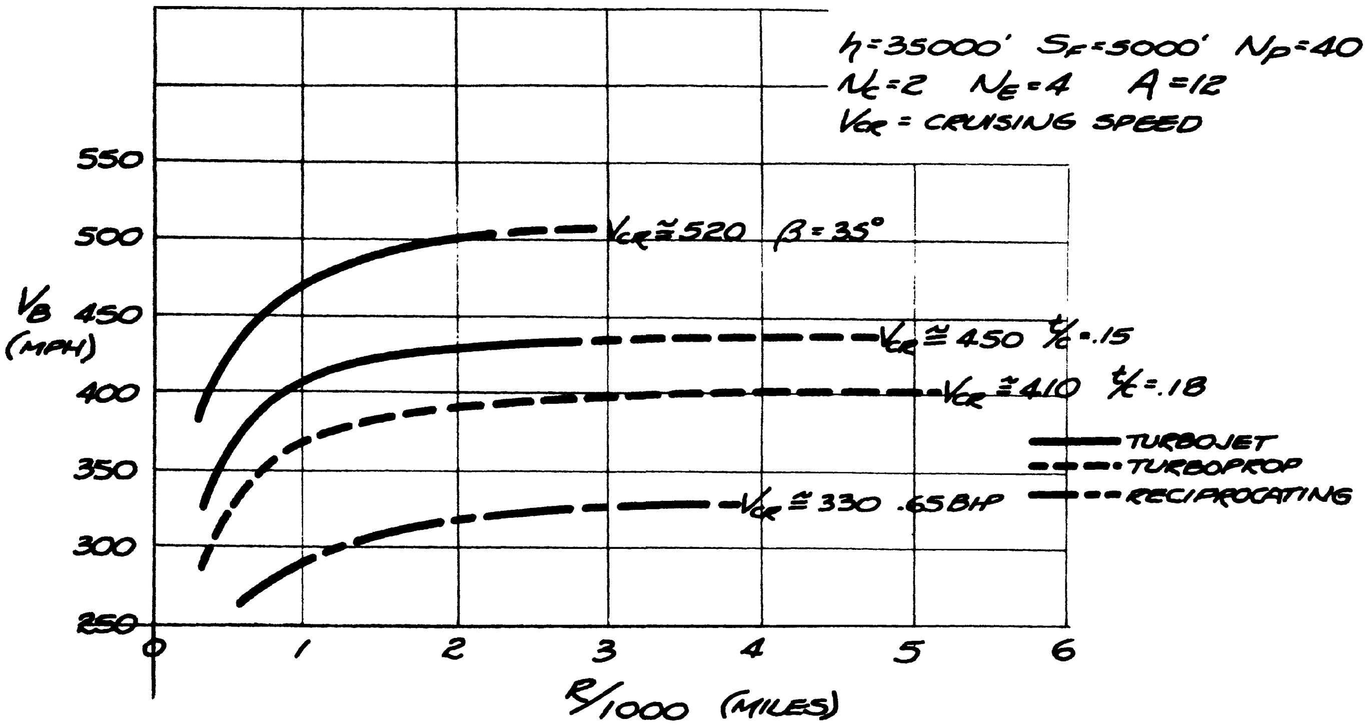


FIG. 21



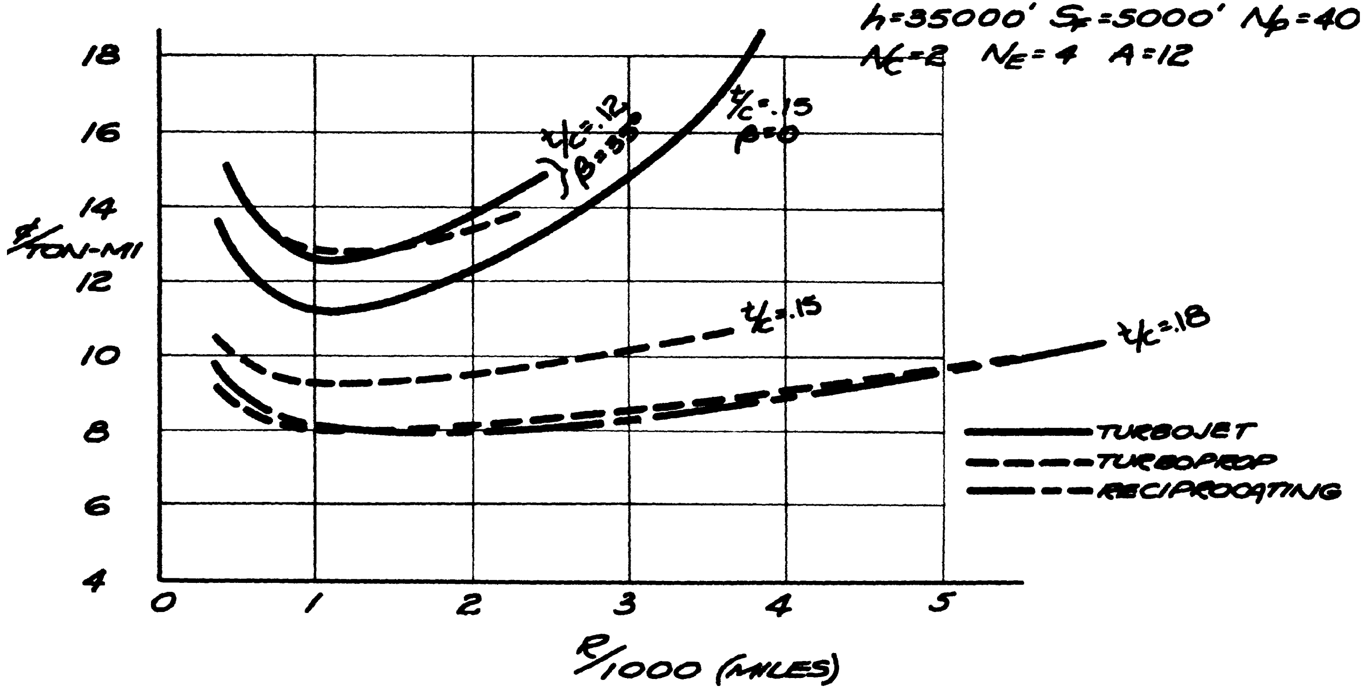
WEIGHT vs RANGE

FIG. 22



BLOCK SPEED vs RANGE

Fig. 23



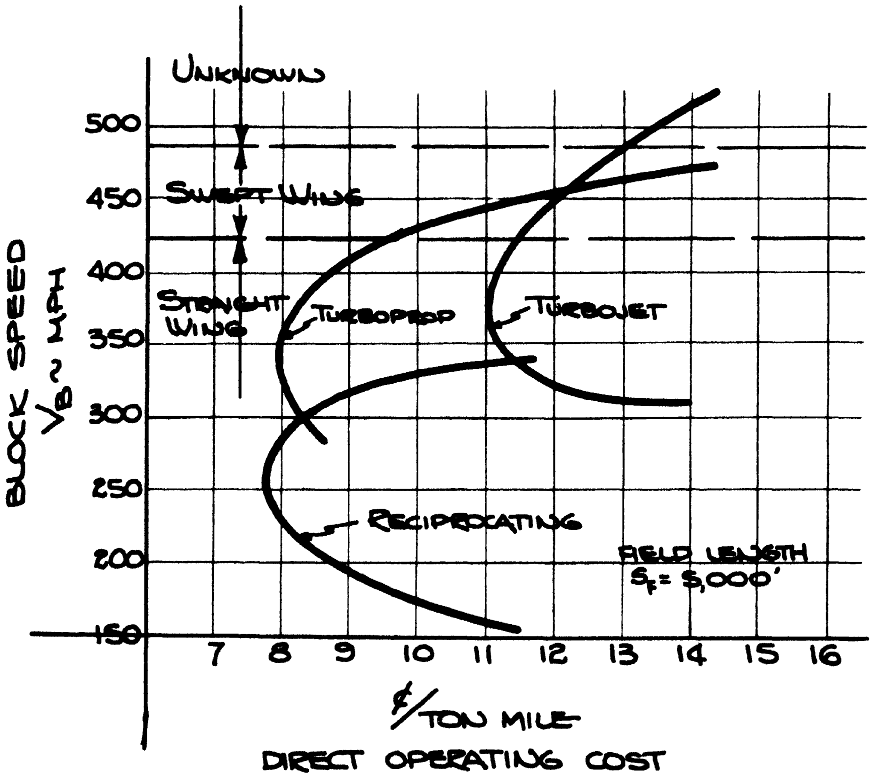
COST vs RANGE

FIG. 24

cruising speeds than three hundred mph are gained only by a progressive penalty in direct operating costs. If a 500-525 mph cruising speed ($V_B = 470$) is desired, the turbojet transport would be a logical selection. On the other hand, a turboprop design would be a logical selection for a cruising speed of 400 mph ($V_B = 350$) and would be considerably cheaper to operate. However, the development of this engine is approximately two to three years behind the turbojet and could never be used at speeds approaching 500 mph unless suitable high-speed propellers are also developed.

Figures 26 and 27 present a typical breakdown of fuel used and show how this affects direct operating costs for the three types of transports considered. It is noted that the fuel consumed in the case of the turbojet airplane is over four times that for the reciprocating type airplane and over twice that for the turboprop airplane. More severe holding conditions at low altitudes would tend to magnify this difference. These fuel consumptions are reflected in Figure 27 in the direct operating cost breakdown. It would appear from this picture that it might pay the oil companies to subsidize the development of turbojet transports.

In order to evaluate the logical selection of the jet transport of tomorrow, it is necessary at this point to determine the estimated total cost of operation for these three different types. In the following tabulation is



COST vs SPEED

RANGE = 1000 Mi

FIG. 25

FUEL BREAKDOWN

RANGE ≅ 1000 Mi
PASSENGERS = 40
FIELD LENGTH ≅ 5,000'

	RECIPROCATING	TURBOPROP	TURBOJET
CLIMB	1600	1000	3230
CRUISE & MANEUVER	2800	6400	11,900
RESERVE (3/4 HR + 200 Mi)	1200	2800	8,650
TOTAL	5600	10,200	23,780
CRUISE SPEED	300	440	500

FIG. 26

presented an approximate financial summary of five representative airlines in the United States for the year 1946. It is noted from this comparison that indirect operating costs averaged over fifty per cent greater than the direct operating costs for this same period. Half of these indirect costs can be attributed directly to wages paid to airline personnel other than flight crews. This means that out of every dollar spent by the airlines twenty-five to thirty cents is spent for these payroll expenses. Indirect expenses can be attributed in general to equipment maintenance (e.g. offices and hangers), ground operations, passenger service (e.g. reservation systems), advertising, public relations, training programs, and general administrative expenses. It is difficult to evaluate the effect of speed and type of transport on indirect operating costs, and for a preliminary estimate these expenses are assumed to be constant for all types and equal to an average based on 1946 airline data of approximately twenty-eight cents per ton mile or 2.8 cents per passenger mile. Based on these data Figure 28 presents the relative airline fare for the three different types of transports previously discussed. Here again the overall operating cost for the turbojet is above that for the turboprop and reciprocating transports, but the difference is less than ten per cent. The premium to be paid for high speed in this case is not great, and a further discussion of some of the more abstract aspects of speed may make the turbojet transport an attractive possibility.

BREAKDOWN OF DIRECT OPERATING COST

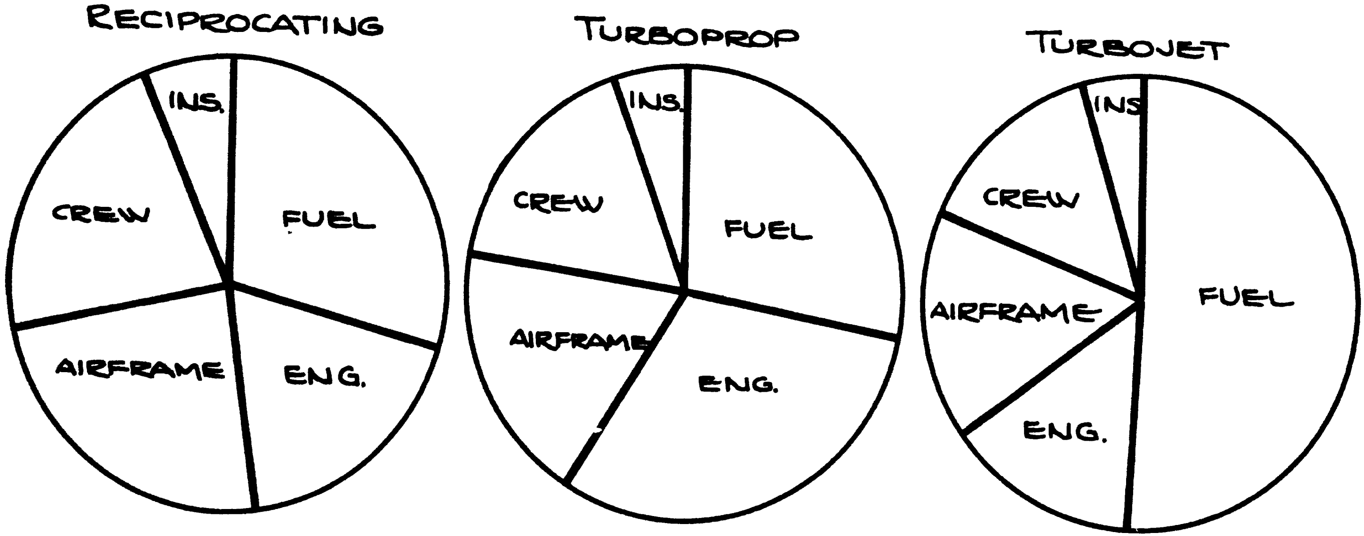
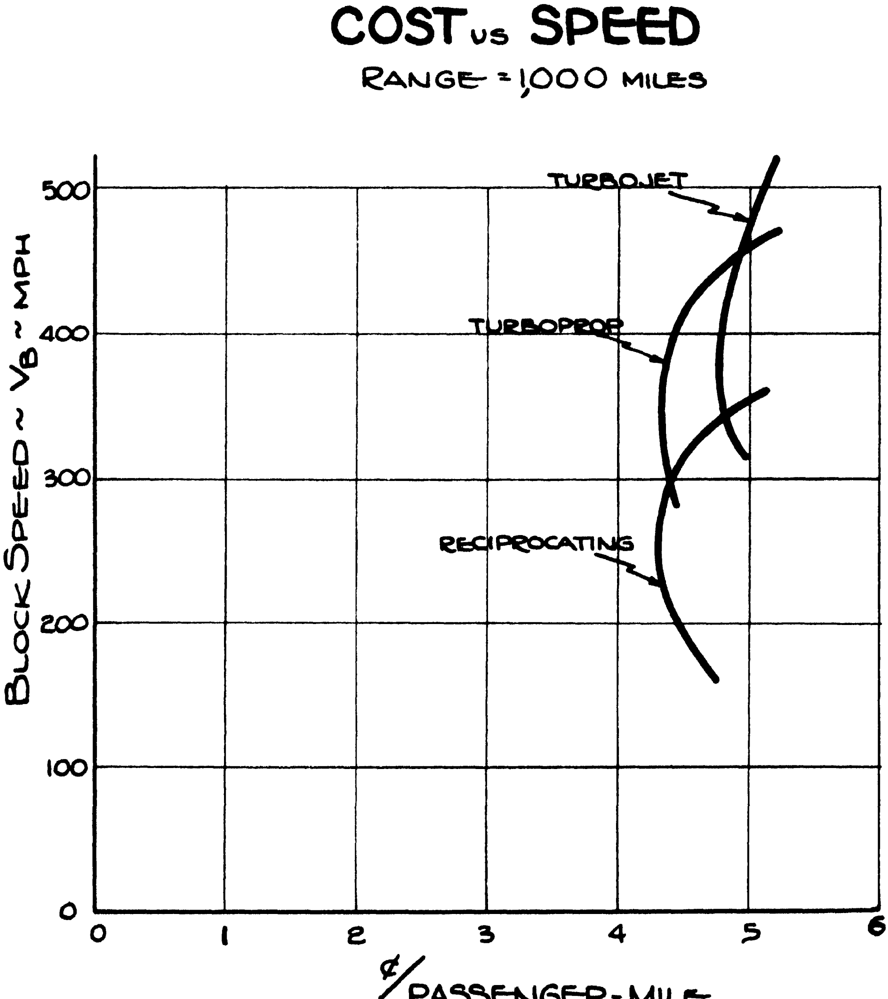


FIG. 27



REQUIRED PASSENGER FARE WITH .4¢/PASS. MI. PROFIT INCLUDED

FIG. 28

1946 FINANCIAL SUMMARY
(Millions of Dollars)

Excerpt from American Aviation Daily, April 25, 1947

AIRLINE	Total Revenue	Direct Operating Expense	Indirect Operating Expense	Ratio Indirect to Direct	Net Profit Or Loss	Total Assets
American	68.0	26.3	42.0	160	- .25	128.0
Northwest	19.3	7.8	11.6	149	- .05	19.2
Eastern	41.6	14.9	18.5	124	3.6	36.8
United	55.9	20.9	34.0	163	1.8	55.0
TWA	40.4	18.7	31.3	168	-8.3	67.8

In presenting the case for the turbojet transport in the following discussion it is assumed that engine availability would permit the practical use of such a transport within three years, provided the operational facilities on the airlines will improve during this period. It is predicted that at least four turbojet power plants with maximum static thrust ratings of between 5000 and 8000 pounds will be available for commercial operation in this country and England in this same period of time. As has been previously discussed, the case for the turboprop engine is not so favorable. The requirements of this engine, a high speed propeller and high ratio reduction gears, will probably put the availability of such a combination at least five years away. Furthermore this combination will not produce a transport with as favorable a speed margin as the turbojet power plant. Therefore, a case for the jet transport of tomorrow will be built around the use of a turbojet power plant.

In determining the design range of such a transport a study of the total passenger miles flown versus length of trip is desirable. This traffic potential is dependent on the distances between major centers of population within the United States. In Figures 29 to 33 are presented the principal schedule stops for five representative lines operating in this country. The average trip distance between major centers of population based on these maps is approximately 450 miles. Figure 34, based on 1946

traffic data, shows the per cent of total passenger miles flown by all the major airlines (including international stops) plotted against flight distance. As a function of the non-stop range of flight, a jet airplane designed to operate efficiently with full payload for ranges between 250 and 1000 miles would pick up fifty per cent of the total business. If at the same time this airplane could operate efficiently on transcontinental runs, assuming two stops, an additional thirty per cent of the total business would be generated. The block-to-block speed of such a transport versus range is illustrated in Figure 35. Even for transcontinental runs the block speed of the jet transport is greatly superior to the best reciprocating engine airplane of today.

As a result of the study of these block speeds, it appears that the selection of a jet transport with a design range of approximately a thousand miles would service all domestic runs from 250 miles to 2500 miles. This would permit the airlines to concentrate on the development of one type of airplane that would service 80 per cent of the available traffic. Large long-range airplanes like the Constellation, DC-6, and the Stratocruiser would still be desirable for transocean operation and to a limited extent for non-stop transcontinental operation. The use of the jet airplane to feed traffic to and from these ocean airliners would tend to stimulate business for the latter type of airplanes due to the efficient manner in which the major

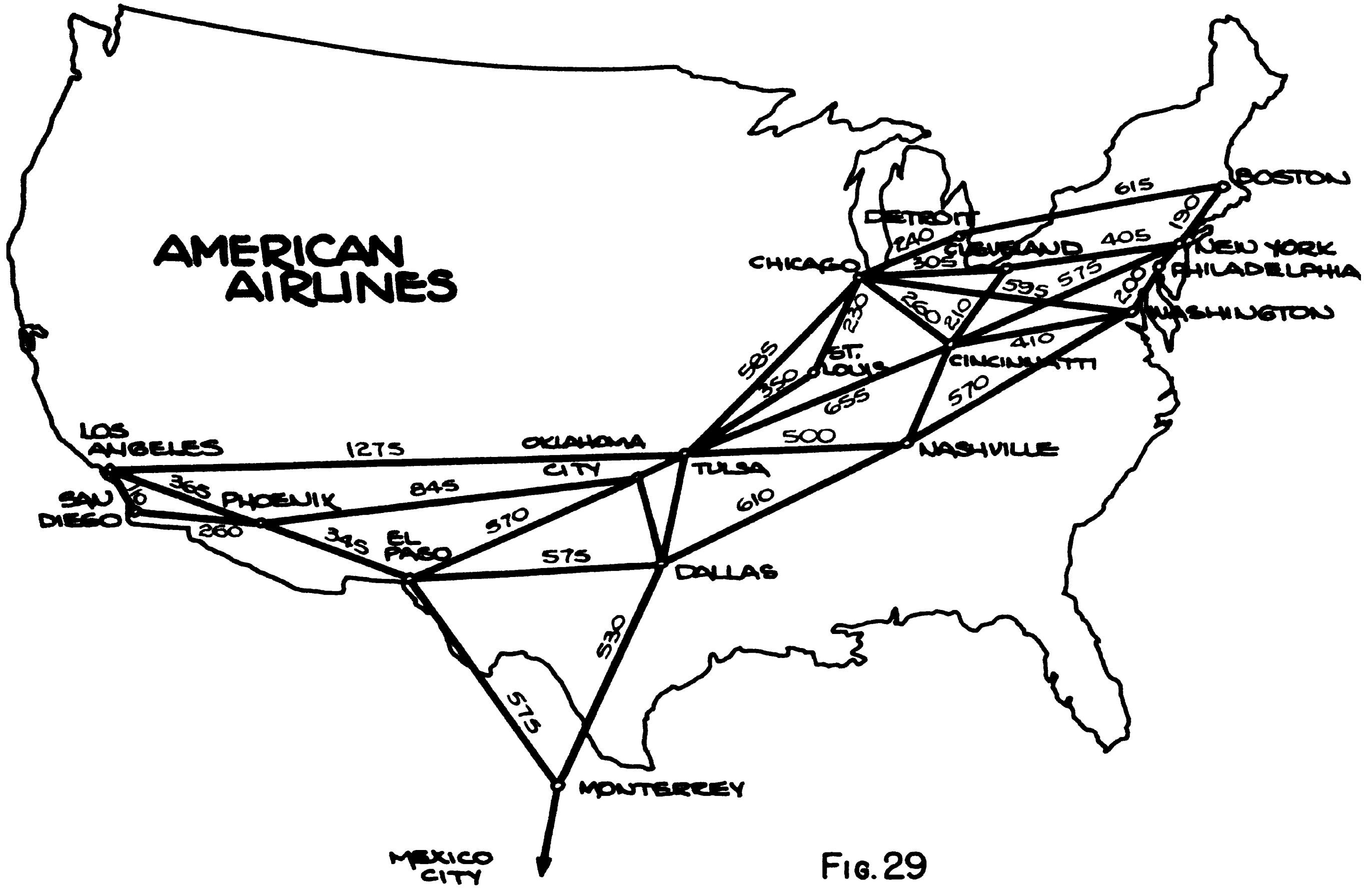

AMERICAN AIRLINES
BOSTON
NEW YORK
PHILADELPHIA
WASHINGTON
DETROIT
CLEVELAND
CHICAGO
CINCINNATTI
ST. LOUIS
NASHVILLE
LOS ANGELES
OKLAHOMA CITY
TULSA
SAN DIEGO
PHOENIX
EL PASO
DALLAS
MONTERREY
MEXICO CITY
615
190
405
240
305
575
595
200
260
210
230
410
585
350
655
570
500
1275
365
845
110
260
345
570
575
610
530
575

FIG. 29

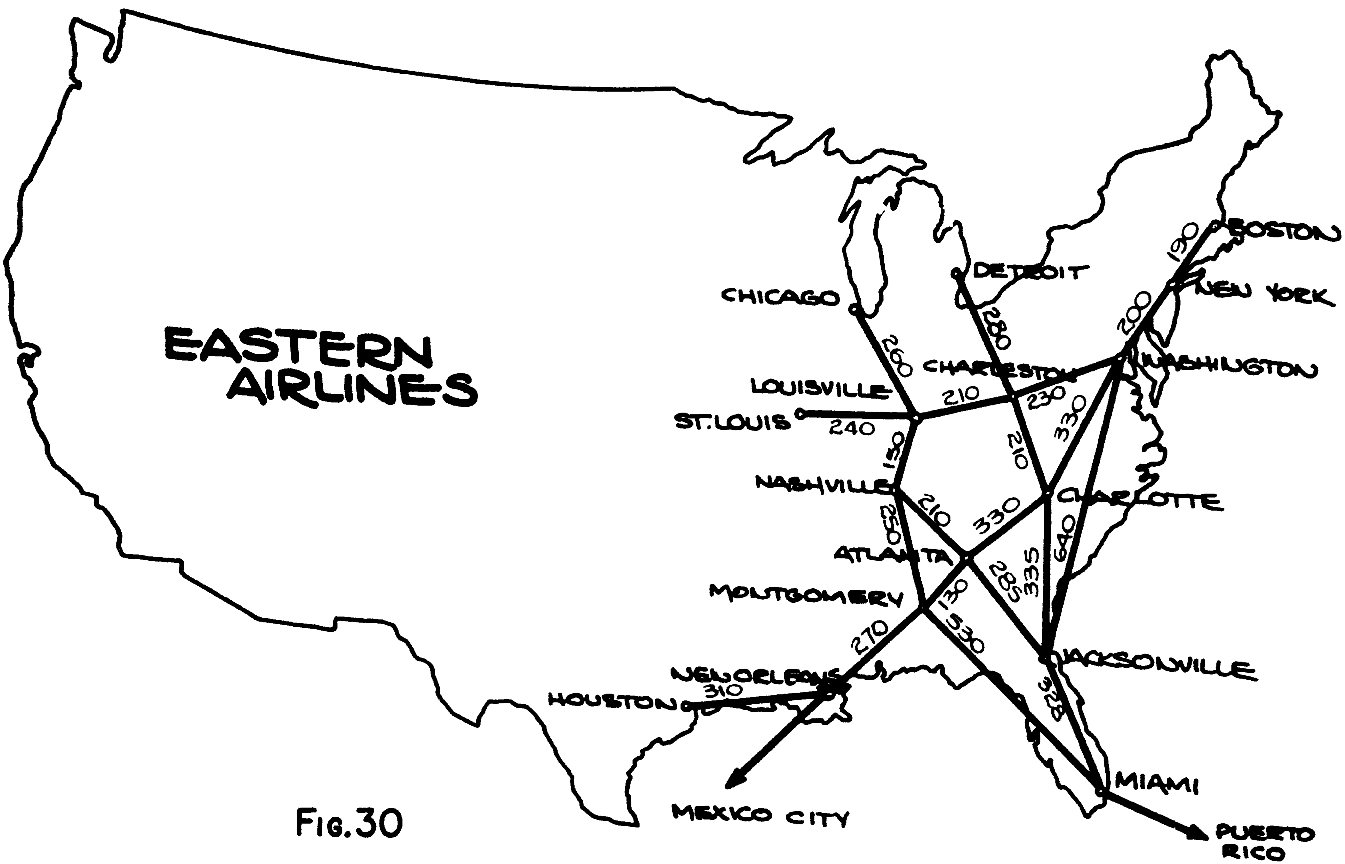

EASTERN
AIRLINES
BOSTON
NEW YORK
WASHINGTON
DETROIT
CHICAGO
CHARLESTON
LOUISVILLE
ST. LOUIS
NASHVILLE
CHARLOTTE
ATLANTA
MONTGOMERY
JACKSONVILLE
NEW ORLEANS
HOUSTON
MIAMI
MEXICO CITY
PUERTO
RICO
190
200
280
260
210
230
330
240
130
210
250
210
330
640
335
285
130
530
270
310
328

Fig. 30

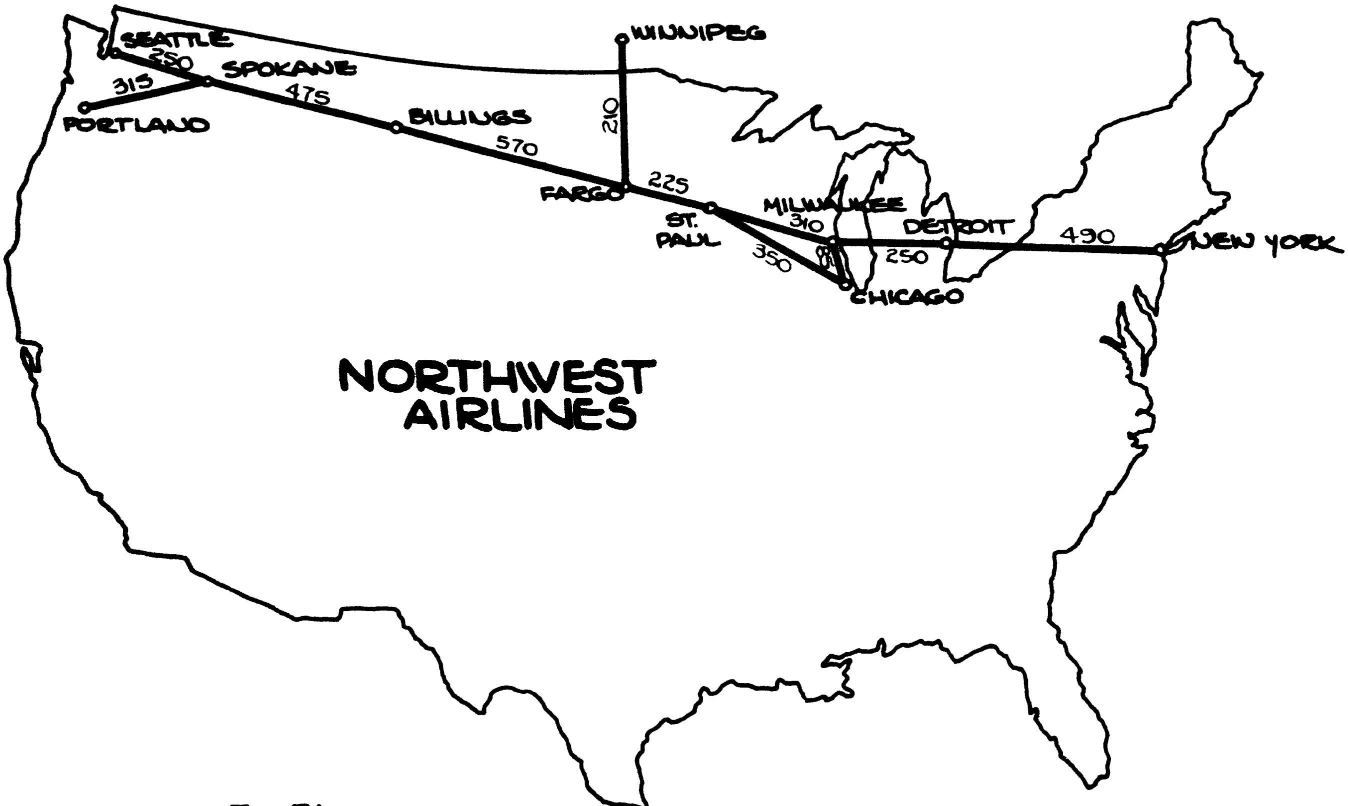

SEATTLE
250
SPOKANE
315
PORTLAND
475
BILLINGS
570
WINNIPEG
210
FARGO
225
ST. PAUL
MILWAUKEE
310
350
CHICAGO
DETROIT
250
490
NEW YORK
NORTHWEST AIRLINES

Fig. 31

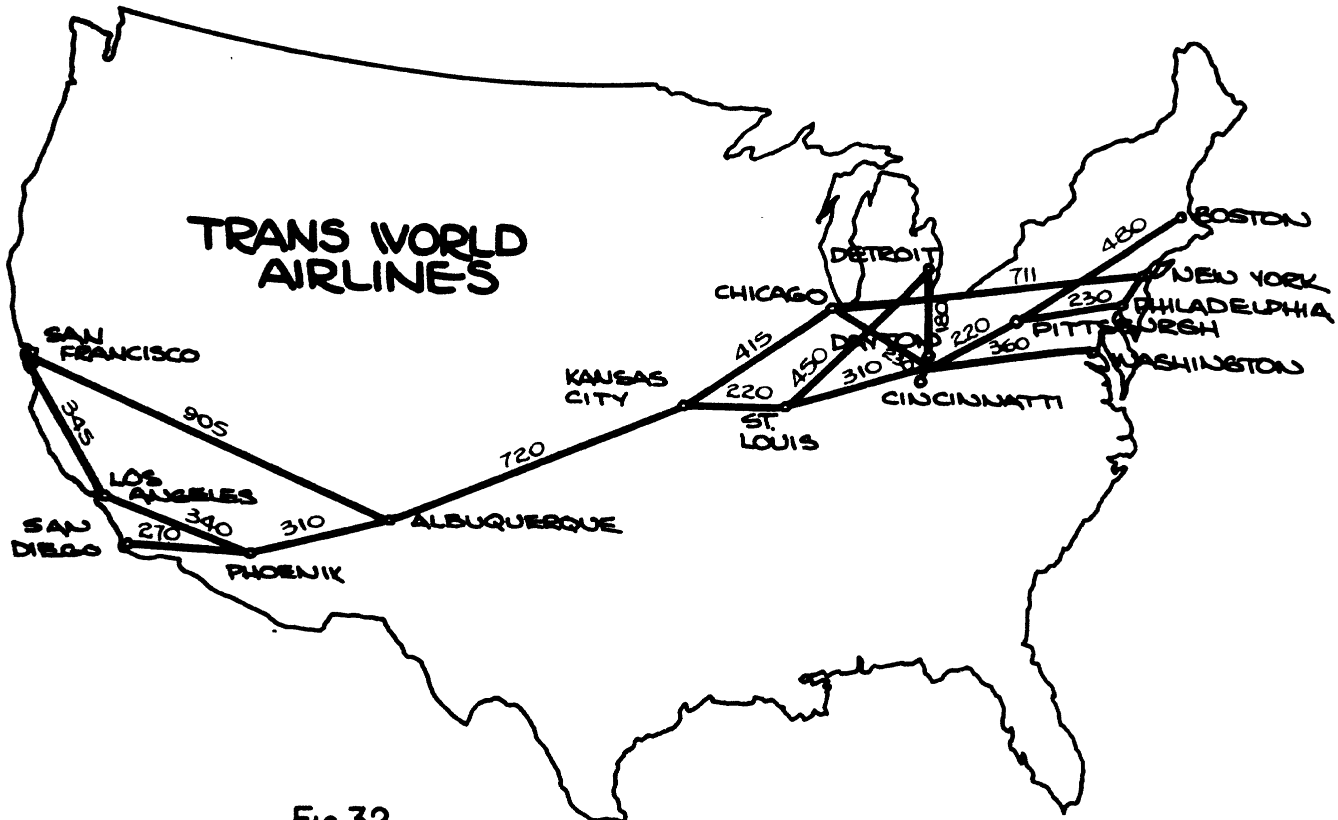

TRANS WORLD AIRLINES
SAN FRANCISCO
LOS ANGELES
SAN DIEGO
PHOENIX
ALBUQUERQUE
KANSAS CITY
ST. LOUIS
CHICAGO
DETROIT
CINCINNATTI
PITTSBURGH
BOSTON
NEW YORK
PHILADELPHIA
WASHINGTON
345
905
270
340
310
720
415
220
450
310
180
220
360
711
230
480

FIG.32

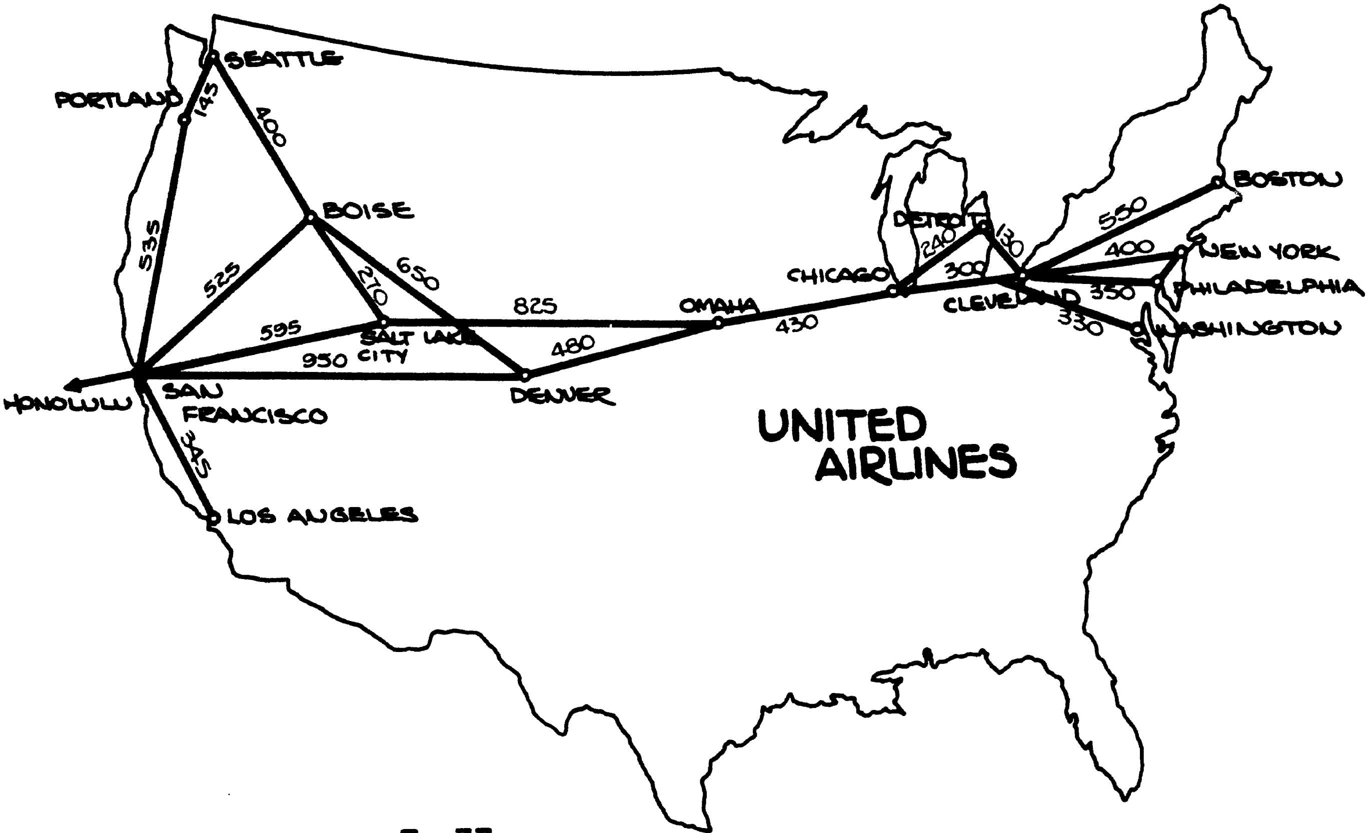

SEATTLE
PORTLAND
145
400
BOISE
535
525
270
650
825
OMAHA
430
CHICAGO
DETROIT
240
300
130
CLEVELAND
550
400
350
330
BOSTON
NEW YORK
PHILADELPHIA
WASHINGTON
595
SALT LAKE
CITY
950
480
DENVER
HONOLULU
SAN
FRANCISCO
345
LOS ANGELES
UNITED
AIRLINES

FIG. 33

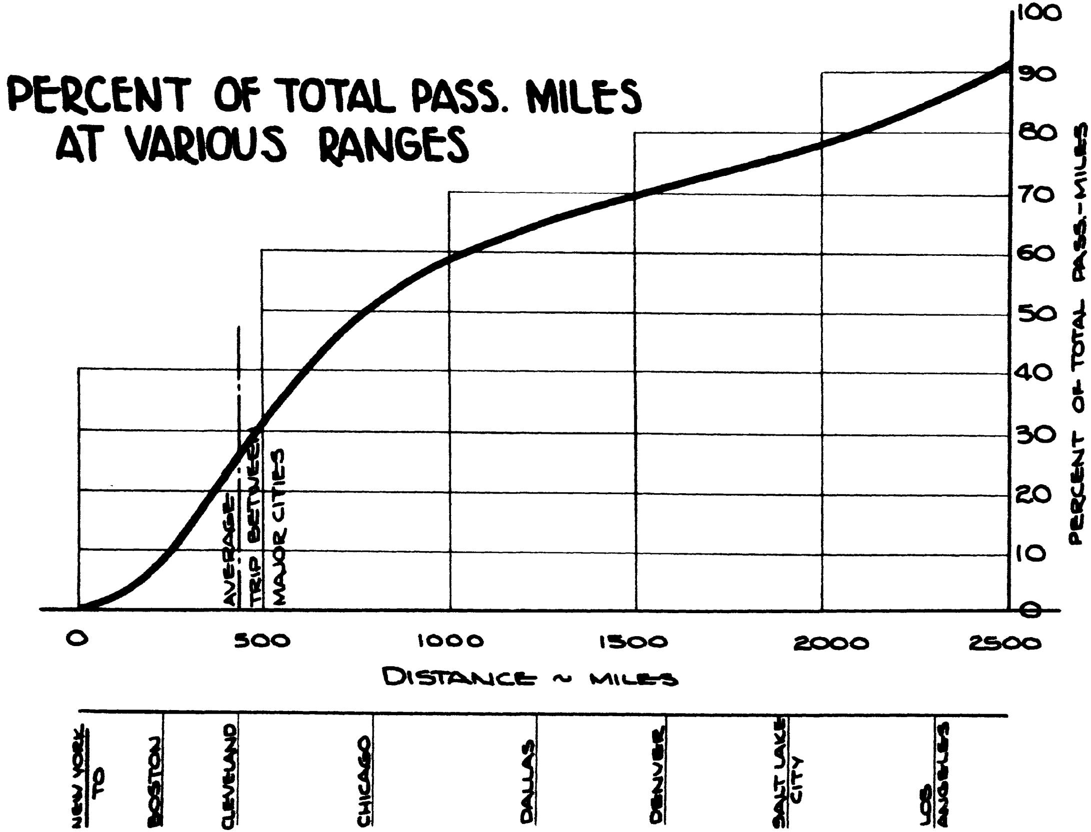

PERCENT OF TOTAL PASS. MILES
AT VARIOUS RANGES
PERCENT OF TOTAL PASS.-MILES
0
10
20
30
40
50
60
70
80
90
100
DISTANCE ~ MILES
0
500
1000
1500
2000
2500
AVERAGE
TRIP BETWEEN
MAJOR CITIES
NEW YORK
TO
BOSTON
CLEVELAND
CHICAGO
DALLAS
DENVER
SALT LAKE
CITY
LOS
ANGELES

FIG. 34

BLOCK SPEED vs. FLIGHT DISTANCE

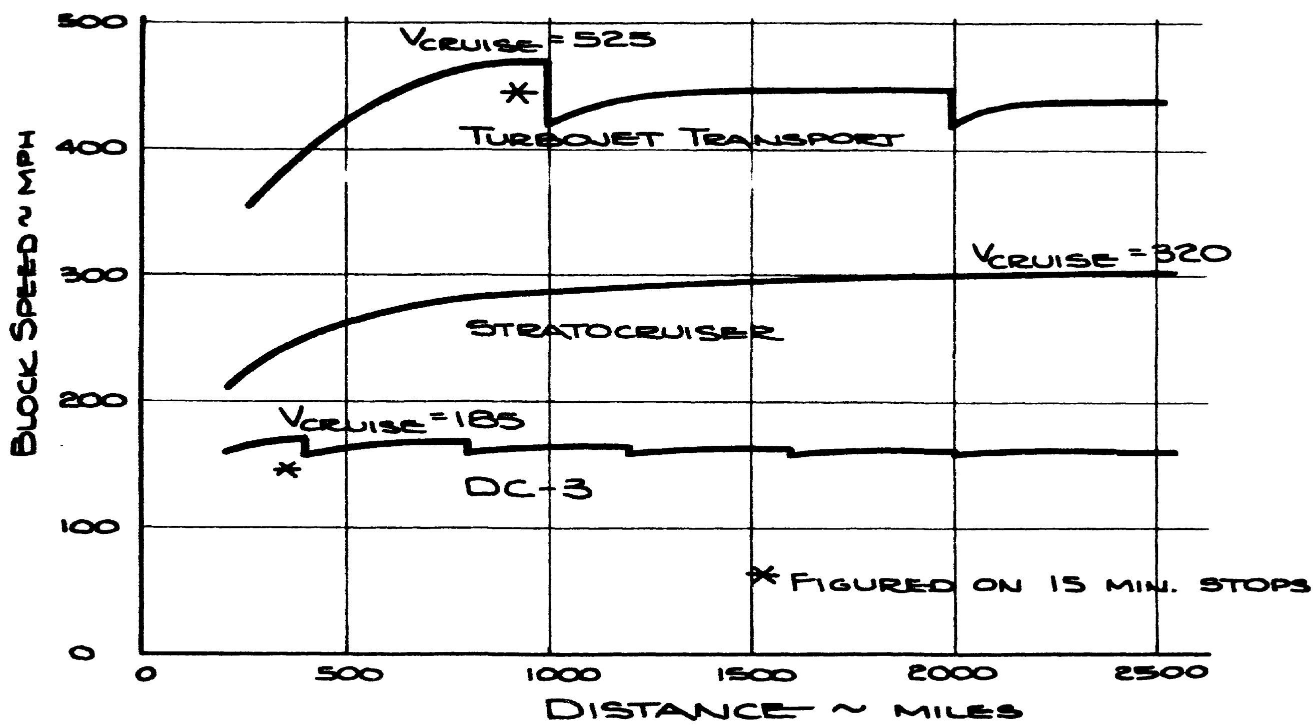


FIG. 35

centers of domestic population would be connected to the ocean routes. A feeder type airplane like the DC-3 or a suitable replacement would still be necessary for short runs less than 250 miles and within lightly populated areas of the United States for even longer ranges. In effect, then, over seventy five per cent of the airplanes could be of the turbojet type. The effect of reducing the number of types of airplanes used by any one airline would certainly reduce indirect operating expenses. The cost of training personnel and the cost of maintaining special equipment and facilities would be reduced.

In determining the effect of block speed on passenger capacity or the number of airplanes that would be required to handle effectively the air passenger traffic, an examination of Figure 36 is useful. In this figure it is shown that the effect of an increase in block speed for any given type and size of airplane reduces the number of airplanes necessary to handle a given number of passenger miles. For example, approximately eleven hundred DC-3's would be required to handle ten billion passenger miles per year at seventy per cent payload assuming ten hours per day utilization of the airplane. For the same number of passenger miles per year, less than two hundred Stratocruisers would be required. Since this number of airplanes would probably operate for a five year period, assuming that each airplane is depreciated over this period of time, it is possible that a relatively small number of large jet

transports would soon flood the market. Therefore, it is desirable that the passenger capacity for this type of transport be reduced to a relatively small number, preferably less than thirty. Furthermore, the frequency with which a small jet transport could operate would be much greater with this small passenger capacity. The effect of high block speed naturally dictates more frequent schedules provided the passenger capacity of each airplane is kept to a practical minimum. The maximum frequency with which airplanes could operate from an airport such as LaGuardia may dictate the minimum practical size of the future jet transport. The effect of high-speed high-frequency schedules would tend to generate more business and would also permit skip-stop schedules so that every major center of population would be adequately serviced each day.

The effect on indirect operating costs of high-frequency low-capacity operation would probably be favorable. Inasmuch as approximately thirty per cent of the total operating costs of an airline can be traced directly to ground personnel wages, any reduction in numbers of personnel would favorably affect total operating costs. For example, a sixty passenger airplane requires a certain fixed number of personnel on the job for an eight hour period even though this number is useful or required during only a small portion of this time when the planes are arriving or departing from an airport. The same number of passenger miles could be served by a smaller number of personnel on

EFFECT OF BLOCK SPEED (V_B) ON PASSENGER CAPACITY

10 BILLION PASS. MILES PER YEAR @ 70% PAYLOAD
10 HOURS PER DAY UTILIZATION PER AIRPLANE

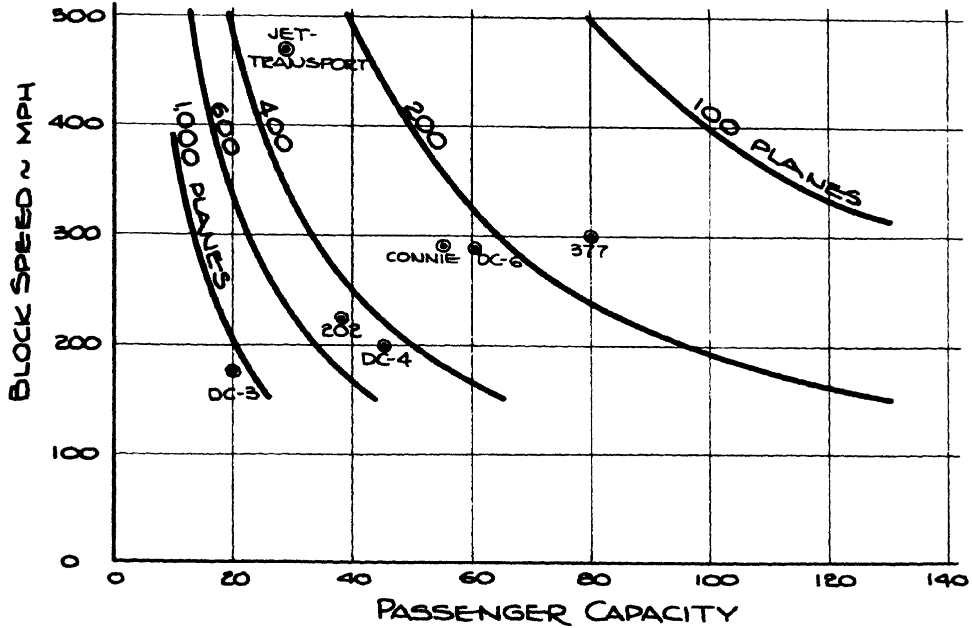


FIG. 36

the job for the same length of time by servicing a greater number of departures and arrivals of the smaller higher speed airplanes. Another factor that is of some importance in cutting down indirect costs is the reduction in all-night operations. For example, a jet transport could be scheduled to arrive no later than midnight for any route within the United States and yet offer a multiple choice of departure times from any major center of population.

Figure 37 presents the effect of scheduled block time on distance. The possible saving in time associated with jet schedules can only be evaluated by the individual passenger. Where loss in time is costly, as it is for many businessmen, the desirability of the jet transport schedules is quite obvious. If at the same time this type of transport maintained or even improved present standards of reliability, safety, and comfort, then there would be little argument for slower types of transports.

The schedule speeds represented in Figure 37 are somewhat lower than the block speeds previously discussed, due to allowances made for prevailing winds and minor delays en route.

To evaluate the effect of winds on block speed, a study of Figure 38 is necessary. Based on United Airlines data, this figure indicates the maximum and mean wind velocities versus altitude and a typical distribution of these winds at an altitude of 18,000 feet. Assuming a westerly wind of eighty-five miles per hour at the operating altitude (35,000 feet) of the jet transport, and assuming for

BLOCK TIME vs FLIGHT DISTANCE

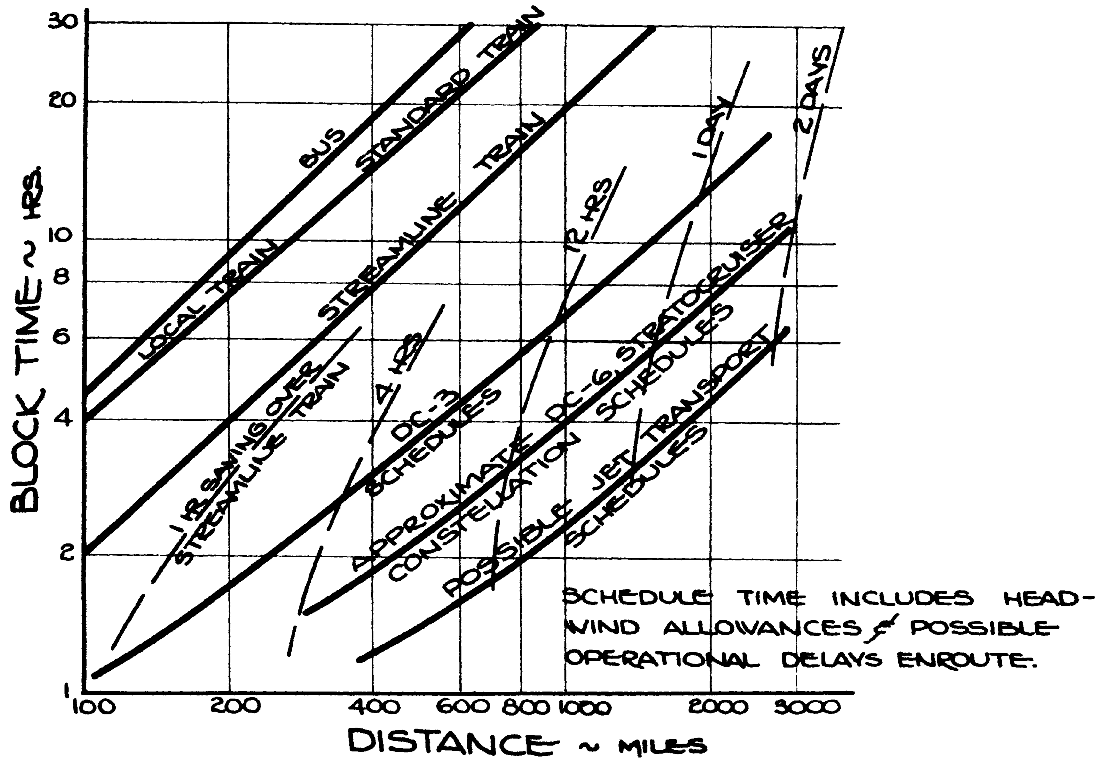
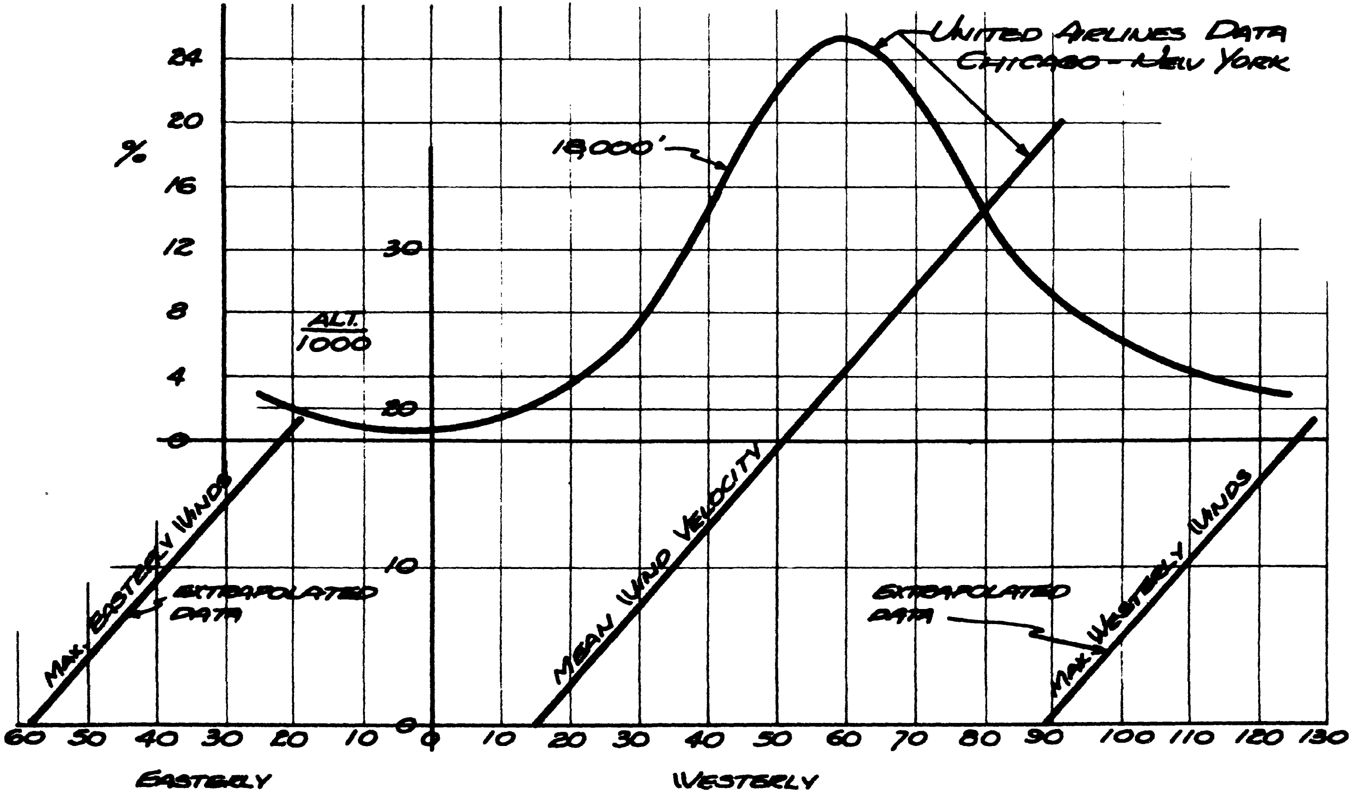


FIG. 37

scheduling purposes a fifteen mile per hour correction in the conservative direction, a westerly wind of eighty-five minus fifteen or seventy mph is assumed for eastbound flights, and an eighty-five plus fifteen, or a one hundred mph westerly wind is assumed for westbound flights. At a thousand miles range, this would increase the block speed for eastbound flights from a zero wind speed of 470 mph to approximately 530 mph and decrease the block speed for westbound flights to approximately 400 mph. Even though the mean wind velocity increases with altitude, the effect of a high cruising speed associated with a jet transport tends to alleviate the effect of head winds.

At the present stage of the art, the airplane designer can anticipate no decrease in safety for the high speed transport cruising at 525 miles per hour provided a margin of at least fifty miles per hour between this speed and critical speed is maintained. The approach and landing speeds of such an airplane could be made comparable to existing four-engine equipment.

At the same time it is realized that the operational difficulties associated with relatively high density traffic will necessitate improvement in traffic procedures and an increase in the number of landing fields so that the jet transport of tomorrow will not be required to maneuver in a holding procedure before landing. Also, to justify the fast schedule the factor of weather must be eliminated. This means that the successful operation of blind landing



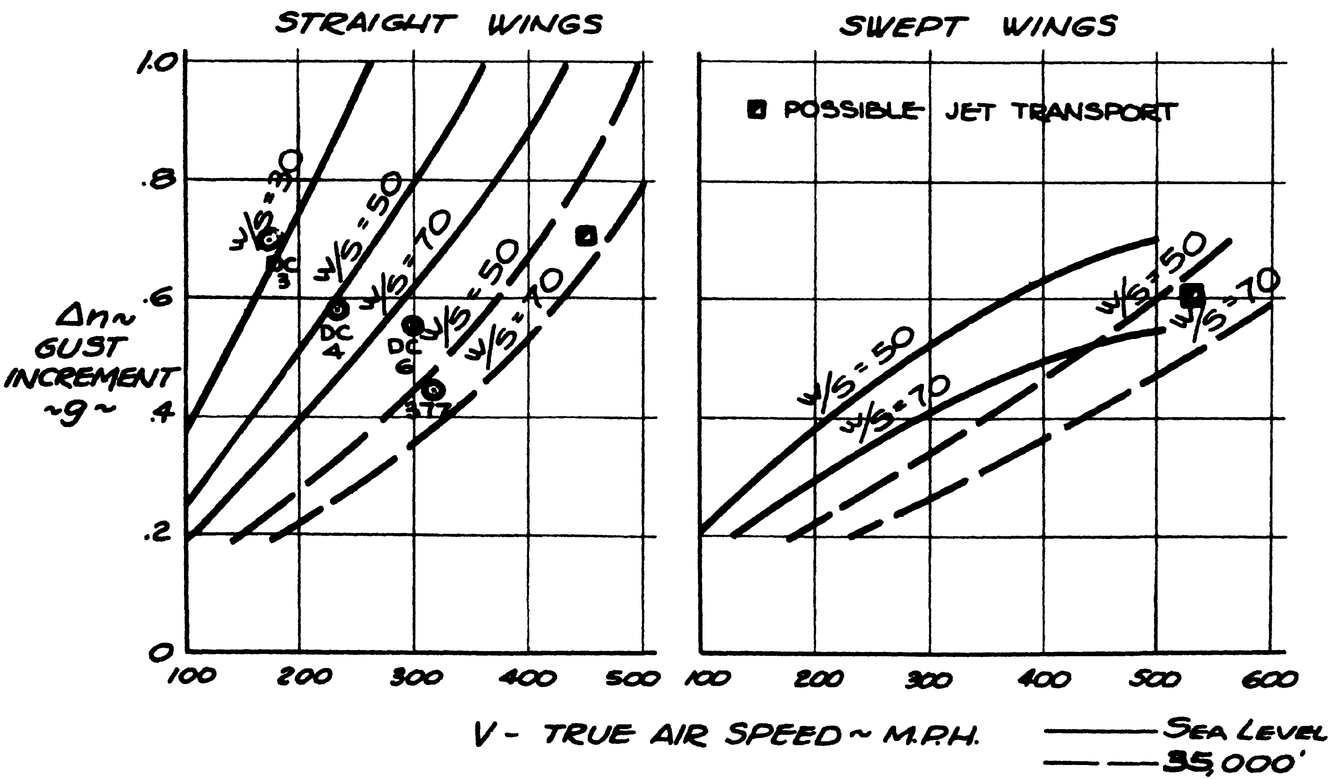
PREVAILING WINDS

Fig. 38

equipment and procedures such as G.C. A. and/or I.L.S. will be necessary. From a passenger comfort standpoint the reduction of vibration due to the elimination of the propeller and reciprocating engine should eliminate some of the unfomfortable physiological effects now associated with air travel. As far as gusts are concerned, Figure 39 illustrates the effect of swept wings for alleviating the normal acceleration produced by a ten foot-per-second gust. The load relieving effect of a swept wing due to the reduction in the slope of the lift curve and the bending of the wing is of course desirable from a passenger comfort standpoint. Even though the jet transport is flying nearly twice as fast as the DC-4, the effect on passenger comfort is comparable to this airplane. It is believed also that the frequency and possibly the magnitude of gusts at the cruising altitude (35,000(ft) of the jet transport will be reduced over that at the cruising altitudes of the DC-4 (5000 - 10,000 ft). Assuming that sound-proofing technique is also improved during the next three years, the air passenger of tomorrow will travel at high speed and in great comfort. The effect of speed in itself tends to promote more passenger comfort as the maximum flight duration between stops is reduced to less than two hours.

The high speed of this type of transport will also permit smaller numbers of transports to service a given number of passenger miles in a given time. Smaller fleet sizes would allow the airlines to decrease such indirect costs as

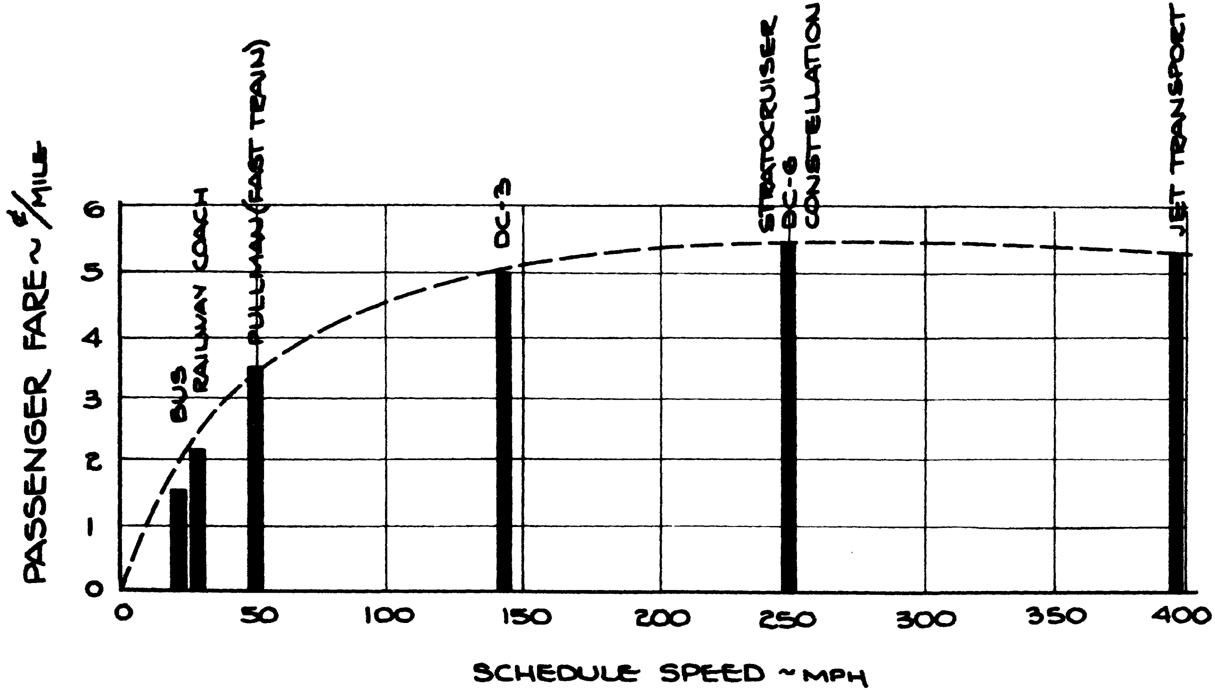
EFFECT OF 10 F.P.S. (I.A.S) GUST



the maintenance of ground flight equipment and hangar facilities. Assuming transports of the same payload, the fleet size requirements for a given earned income would be inversely proportional to block speed.

By approximating the possible decreases in indirect operating costs associated with a small high-speed airplane, a survey of passenger fares and scheduled speeds for present day transports and a prediction of what is in the offing for the jet transport of tomorrow is presented in Figure 40. It is believed that the fares for the jet transport will actually be lower than the premium fares now charged on some of the present airlines.

A series of range-payload curves associated with the type of airplane depicted at the end of Chapter I are presented in Figure 41. Weight limitations are based on engine thrust outputs varying from what should be available for a prototype airplane within one year (To_M = 6000 lbs) and what should be available by the close of the year 1950 (To_M = 8000 lbs) and limiting values of W/S and W/To_M as determined from Figure 21. The maximum weight of a production article with two units (maximum rating 7000-8000 lbs each) would not exceed 60,000 lbs and would require a field length less than 5500 ft. The prototype airplane would be approximately 45,000 lbs in weight and require a field length less than 4500 feet. These curves represent airplane characteristics assuming present day standards for engine fuel consumption and airplane cleanness. Considerable improvement in range



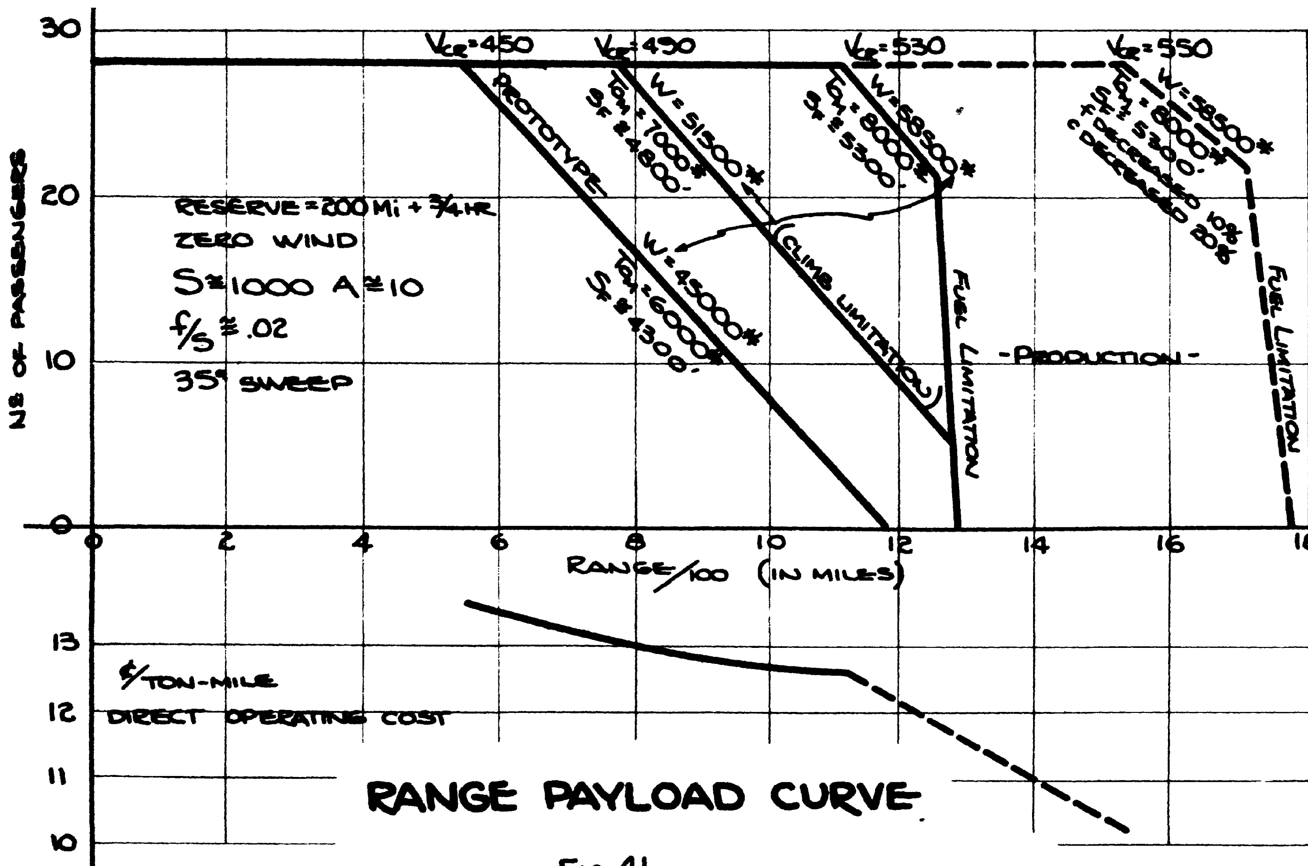
SCHEDULE SPEED vs PASSENGER FARE

RANGE ≈ 1000 MI

FIG. 40

and operating costs could be made if improvements in equivalent parasite area and specific fuel consumption were realized in the next few years. During the next three to four years a maximum decrease in equivalent parasite area of ten per cent is possible, whereas a maximum decrease in specific fuel consumption of twenty per cent is very probable. The development of the turbojet power plant is still in its infancy and forthcoming improvements in fuel consumption, thrust outputs, and reliability foretell a great future for the jet transport. The dashed lines in Figure 41 indicate a range-payload curve assuming a 10 per cent improvement in equivalent parasite area and 20 per cent improvement in specific fuel consumption over present day standards.

It is believed that the development of a prototype turbojet transport as depicted in the preceding discussion would speed the development of turbojet power plants, airport facilities, airline procedures, and the overall efficiency of the American commercial transport system. Most of the problems associated with high-speed flight on the airlines will be solved only when the necessity for these developments is evidenced by an actual prototype transport in trial operation over airline routes.



V_{CR}=450
V_{CR}=490
V_{CR}=530
V_{CR}=550
PROTOTYPE
W=45000#
T_{OH}≅6000#
S_F≅4300'
W=51500#
T_{OH}≅7000#
S_F≅4800'
W=58500#
T_{OH}≅8000#
S_F≅5300'
W=58500#
T_{OH}≅8000#
S_F≅5300'
f DECREASED 10%
c DECREASED 20%
(CLIMB LIMITATION)
FUEL LIMITATION
FUEL LIMITATION
-PRODUCTION-
RESERVE=200 Mi + 3/4 HR
ZERO WIND
S≅1000 A≅10
f/S≅.02
35° SWEEP
N° OF PASSENGERS
RANGE/100 (IN MILES)
¢/TON-MILE
DIRECT OPERATING COST
RANGE PAYLOAD CURVE

Fig. 41

V. LIST OF SYMBOLS

a = speed of sound

A = aspect ratio

A_F = frontal area

AHD = Army Hot Day - °F = 100 at S.L.

b = span

C_L = lift coefficient

C_D = drag coefficient

C_T = thrust coefficient

D = drag

e = efficiency factor for airplane drag

f = equivalent parasite area

F = fuel load

g = acceleration of gravity

GFE = Government Furnished Equipment

h = altitude

hp = horsepower

L = lift

m' = mass flow per second

M = Mach number. (Ratio of speed to speed of sound)

M_{CR} = critical Mach number (Speed at which deleterious lift and drag changes occur due to compressibility effects)

Δn = gust load factor increment

N_C = number of crew

N_E = number of engines

N_p = number of passengers

P = power or payload

q = dynamic pressure

R = range or Reynolds number

S = wing area

S_F = field length

S.L. = sea level

$\frac{t}{c}$ = wing thickness ratio

T = thrust

T_M = military thrust

T_N = normal thrust

T_{o_M} = static military thrust at sea level

v = speed in ft/sec

v_o = freestream speed

v_w = wake or slipstream speed

U.L. = useful load

V = speed in miles/hour

V_B = block speed

V_{s1} = takeoff speed

V_{so} = stall speed

V_{cr} = cruise speed

w = weight flow per second

W = Weight

α = angle of attack

= propulsive efficiency

ρ = mass density of air

= density ratio

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